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LIMING AND FISHERIES MANAGEMENT GUIDELINES FOR ACIDIFIED LAKES IN THE ADIRONDACK REGION

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LIMING AND FISHERIES MANAGEMENT GUIDELINES FOR ACIDIFIED LAKES IN THE ADIRONDACK REGION

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DISCLAIMER

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EXECUTIVE SUMMARY

"Liming" is the general term used for the addition of base neutralizing materials to acidic waters and soils. These can include various base-containing materials, but limestone (calcium carbonate, $CaCO_3$) is predominately used in the major surface-water liming programs in the United States, Canada, and Scandinavia. Liming has long been used to increase fish productivity in softwater and acidic ponds, lakes, and streams; it is currently the principal approach used to mitigate impacts to fish caused by elevated stream and lake acidity due to acid deposition.

This report provides state agencies and private landowners with guidelines useful in evaluating general options available for lake liming and for managing brook trout populations in limed lakes. It begins with a presentation of considerations necessary to determine whether to lime a lake, describing those lake types appropriate for liming and the limitations of liming. Approaches are discussed for determining the appropriate timing and dosages of basic materials to use for liming and reliming lakes. It next summarizes results from the "Extensive Evaluation of Lake Liming, Restocking Strategies, and Fish Population Response in Acidic Lakes Following Neutralization by Liming," commonly called the "Extensive Liming Study" (ELS), which was conducted by researchers from Cornell University and sponsored by the U.S. Fish and Wildlife Service and the U.S. Environmental Agency. The report then considers appropriate stocking and management strategies for brook trout in limed Adirondack lakes. While this report focuses primarily on neutralizing acidic lakes in the Adirondack region, many of the management implications can be extrapolated to other areas.

Agricultural limestone was used for the fall limings of the ELS lakes. Lake water pH, acid neutralizing capacity (ANC), and calcium levels increased significantly immediately following liming. Over the subsequent years, changes occurring in the measured chemical variables indicated that climatic, meteorologic, and hydrologic events had a dominating influence on water qualities in these lakes. This was particularly evident for aluminum and pH.

While there were short-term changes in the species of aluminum in the ELS lakes following liming, little effect on total aluminum concentrations was apparent over the long term. The persistence of high total aluminum levels was not expected based on previous liming experience, which showed that dissolved metal concentrations generally decrease markedly after liming. Persisting aluminum concentrations in the ELS lakes appeared to be primarily influenced by seasonal hydrologic events in the watershed. Low water temperatures during the first six months after liming also may have contributed to the persistence of post-treatment aluminum concentrations by slowing hydrolysis and precipitation reactions. While metal solubilities changed due to liming have been found to

adversely impact fish in some instances, no such impacts were observed in the ELS lakes.

Water transparency markedly decreased following liming in only Mountain Pond, and then only during the first summer following liming. This decrease led to lower water temperatures and a temporarily improved habitat for trout in the deeper waters of this pond.

The ELS lakes were stocked using two groups of interstrain hybrid brook trout: Temiscamie x domestic brook trout selected for presumed tolerance to acidity, and Temiscamie x un-selected domestic brook trout. The two groups showed no consistent differences in survival or growth among the lakes. The lack of consistent between group differences may be related to the relatively rapid reacidification of the lakes. The pH levels in several of the ELS lakes decreased to levels apparently intolerable to both strains in less than one year following the single applications of lime to the lakes during this study.

Four chemical variables (pH, ANC, Ca, and Al) were significantly correlated with brook trout survival in the ELS lakes. Of these, pH marginally had the strongest relationship. Regression analysis of brook trout growth in these lakes, however, indicated that indirect density dependent and/or behavioral related effects also had effects on brook trout survival and growth in the ELS lakes. Slow or negative growth rates may have been caused by reduced food intake by many of the stocked populations. Previous studies in the Adirondacks and in Sweden have indicated that stocked populations in limed lakes can rapidly decimate food resources. Therefore, ELS results indicate that no more than 100 fall fingerling brook trout per hectare (40 per acre) every two years, or 50 per hectare annually, should be stocked into limed Adirondack lakes.

The influence of liming in ELS lakes was compromised by periodic, seasonal inflows of acidic and aluminum bearing waters from the watersheds. This indicates that the success of liming in mitigating the effects of adverse water quality on aquatic organisms depends heavily on meteorologic and hydrologic events controlling the periodic flows of water through lakes. Thus, to best forecast the potential success of liming, it is necessary to quantify as well as possible, prior to liming, the seasonal and annual flushing characteristics (retention times) of candidate lakes.

When contemplating lake liming, the ELS results demonstrate that it is important to establish management objectives that are reasonable expectations considering the resource as a whole. The final success of liming depends, in part, on use of appropriate liming materials at appropriate application rates. Potentials for successful liming can also be limited by high seasonal or annual flushing rates or by continual acidic inputs to the lake via natural or anthropogenic sources. Also, various environmental conditions, in addition to high acidities, can restrict survival, growth, and reproduction of fish populations. These conditions can include the presence of other toxic materials, low basic productivities for food organisms, and limited access or availability to appropriate spawning or rearing habitats. When limitations on populations caused by high acidities are removed, limitations caused by other habitat conditions can then become increasingly important in limiting successful fisheries. Therefore, management goals for a limed lake should be established

in light of available knowledge about the historical fisheries in the lake, on how the dynamics of those fish populations were limited by natural conditions in the lake, and on how conditions now present in the lake may further limit the potential success of liming.

For most limed lakes, the fisheries management objective will be to maintain a fishery as similar as possible to the historical fishery in the lake. A useful starting place in defining fishery management objectives for a limed lake is to determine whether fish populations existed historically in the lake, what fish species inhabited the lake, and whether these species maintained self-sustaining populations or whether they were maintained by stocking. For the Adirondack region, the vast majority of lakes that contained fish were inhabited primarily by populations of brook trout that were maintained by either stocking or natural reproduction.

Results from the ELS lakes clearly show that mean individual growth rates for stocked brook trout were substantially depressed at higher standing crops and densities of brook trout. This relationship highlights the importance of limiting stocking rates in those Adirondacks lakes that are comparable to the ELS lakes. Lower stocking rates reduce foraging pressure on food resources, and lead to significantly better growth in stocked fish. However, growth rates that could be sustained after five or more years of continued maintenance liming and stocking in these low productivity lakes remain unknown. Nevertheless, it is likely that sufficient growth rates can be maintained under lower stocking regimes to establish trophy class brook trout fisheries in some limed lakes in the Adirondacks.

Liming efforts completed not only during the ELS project but also during various other liming projects demonstrate that lake liming is a useful approach for mitigating current and continuing impacts due to surface water acidification. Potential negative impacts to ecosystems from liming appear to be minimal, relative to its potential benefits in improving water quality and associated habitat conditions for fish, other aquatic biota, and terrestrial wildlife.

The Adirondack Lake Survey Corporation found three lakes in the Adirondacks with pH levels below 4.0 and another 619 lakes with pH levels below 6.0. While these acidic lakes comprise 46% of the lakes in the Adirondacks, a relatively low percentage of these lakes meet the combined depth, area, flushing, and other habitat criteria that indicate their suitability for liming. Therefore, while the available results show that liming can improve the water quality for fish and other aquatic biota without adversely impacting natural resources in acidic lakes and streams, there is a somewhat limited potential that operational liming can substantially contribute to enhancing viable habitat for fisheries in the Adirondack region.

A large-scale lake liming program is not an alternative to pollution control. It is an option through which acidification impacts in surface waters can be mitigated until the causes of acidification can be corrected. It is also an approach to mitigate and speed resource recovery following any significant reduction in acid deposition.

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INTRODUCTION

"Liming" is the general term used for the addition of base neutralizing materials to acidic waters and soils. Various base-containing materials may be used, but limestone (calcium carbonate, $CaCO_3$) is predominate in the major surface-water liming programs in the United States, Canada, and Scandinavia (Fraser and Britt 1982). Liming, in fact, has long been used to increase fish productivity in softwater and acidic ponds, lakes, and streams (e.g., Neess 1949, Hasler et al. 1951, Waters 1957, Boyd 1982).

Liming is also currently the principal approach used to mitigate impacts to fish caused by elevated stream and lake acidities, particularly those resulting from acid deposition (Fraser and Britt 1982). Other management approaches, however, could include translocation of sensitive fish species to other more suitable waters, use of fish strains that are tolerant of acidic conditions, and/or use of hatchery fish that have been acclimated to acidic waters (Flick et al. 1982).

Most current surface-water liming efforts underway in the northeastern U.S. and eastern Canada are directed either toward mitigating historical fisheries losses due to acidification, or toward protecting existing fisheries populations from potential stress and loss as a consequence of acidification. Often the goal of <u>mitigative liming</u> is to reintroduce new fish populations or to augment existing populations that have suffered from acidification related impacts; these efforts can lead to new or improved put-and-take, put-grow-and-take, or self-sustaining fish populations introduced to limed surface waters by stocking. <u>Protective</u> or <u>maintenance liming</u> is conducted to lessen the potential for acidification impacts on fish populations having high natural, cultural, or economic importance. Liming also can be valuable in accelerating the establishment of fisheries, for example, in the interval between the increased control of acidic emissions to the atmosphere and subsequent natural recovery of acidified lakes and streams.

Within the United States, the Adirondack Mountains of New York are generally recognized as the region most severely affected by acid deposition. The Adirondack Lake Survey Corporation (Kretser et al. 1989) has found that 351 of 1469 (24.9%) surveyed Adirondack lakes have pH levels less than 5.0, which include lakes acidified by both natural and man-caused sources. Native fish populations have disappeared from many acidic Adirondack lakes (Pfeiffer and Festa 1980; Schofield 1976, 1982), and maintenance of sport fisheries by stocking hatchery reared trout has often been unsuccessful in waters having low pH and high aluminum levels (Schofield and Trojnar 1980).

The combined effects of high acidity, high concentrations of dissolved aluminum, and low concentrations of calcium primarily causes the loss of fish populations from acid lakes (Baker 1982, Bergman et al. 1988, Brown 1981). High

aluminum concentrations in surface waters are mostly caused by its leaching from acidic watershed soils, and the high soil acidities can result from acid deposition (Norton 1982).

Largely in response to the extent of acidic lakes within its state borders, the New York State Department of Environmental Conservation (NYSDEC) has limed lakes as a fisheries management technique since the early 1960s (Blake 1981, 1982). Initially, the neutralizing materials were primarily applied to naturally acidic (dystrophic) bog ponds. Since 1965, however, the NYSDEC liming program has focused on waters thought to have been affected by acid deposition. This program has included over 125 treatments to approximately 60 waters (Kretser and Colquhoun 1984).

While most earlier NYSDEC treatments applied hydrated lime, $Ca(OH)_2$, as the neutralizing material, later treatments emphasized calcite, $CaCO_3$, as the primary material used in the NYSDEC program. Beyond the NYSDEC liming efforts on public lands, additional waters too acidic to support healthy fish populations on private lands in New York have been limed during the past two decades (Flick et al. 1982, Gloss et al. 1988). These efforts provide a substantial history on the effectiveness of liming in New York.

THE EXTENSIVE LIMING STUDY

The "Extensive Evaluation of Lake Liming, Restocking Strategies, and Fish Population Response in Acidic Lakes Following Neutralization by Liming," commonly called the "Extensive Liming Study" (ELS), was conducted through Cornell University and funded as part of the National Acid Precipitation Assessment Program by the U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency. ELS accomplished two primary goals. First, existing information from liming projects conducted in the Adirondacks by NYSDEC and private landowners over the past 25 years was compiled and analyzed (Gloss et al. 1988). Secondly, a pilot scale liming program was completed on ten acidic lakes in the Adirondack region. These liming experiments included four objectives: 1) examine variations in fish population response and liming effectiveness over a range of lakes with differing physical and chemical characteristics; 2) compare and integrate results from ELS lakes with results from other more intensive and comprehensive studies that focused on ecosystem level responses in a small number of lakes; 3) evaluate the success of restocking strategies using fish selected for presumed tolerance to acidic waters; and 4) provide management guidelines for lake liming and fisheries management in limed Adirondack lakes. While introducing and summarizing results and conclusions from the project, this report primarily addresses the fourth objective of the ELS study.

OBJECTIVES OF THIS REPORT

This report provides state agencies and private landowners with guidelines useful in evaluating general options available for lake liming and for managing brook trout populations in limed lakes. In addition to providing a synopsis of results from the ELS, this report presents the considerations necessary to

determine whether to lime a lake. It describes those lake types most appropriate for liming, and discusses the limitations of liming. Procedures are presented for determining the appropriate timing and dosages of basic materials to use for liming and reliming lakes. Finally, considerations are discussed that are necessary during the development of appropriate management and stocking strategies for brook trout in limed lakes.

The liming strategies discussed in the following sections emphasize techniques that involve application of the basic materials directly to surface waters. For some acidic lakes with water retention times of less than 0.5 year and for some acidic streams, liming of the watersheds surrounding the lakes or streams may be more appropriate. These techniques and some of their results have been recently reviewed by Brown (1988) and Warfvinge and Sverdrup (1988a, b).

While this report focuses on acidic lakes in the Adirondack region, many of the management implications could be extrapolated to similar resources throughout the Northeast. Four additional reports available through the U.S. Fish and Wildlife Service augment the information presented in the following sections:

1. Brown and Goodyear (1987) detail methods and protocols useful for planning, implementing, and analyzing liming research projects.

2. Fraser et al. (1985) describe neutralization materials, liming equipment, and mitigative techniques.

3. Schofield et al. (1986) present methods used during the ELS project, show detailed bathymetric maps of the ELS lakes, and examine various chemical and biological changes recorded during the first three years of this liming project.

4. Gloss et al. (1988) review all available liming data from New York state and evaluate this information plus additional information from the ELS lakes in relation to models predicting probable chemical responses by lakes to liming.

GENERAL CONSIDERATIONS AND PROCEDURES FOR LIMING AND MANAGING LIMED LAKES

DEFINING THE OVERALL MANAGEMENT GOALS FOR LIMED LAKES

When contemplating liming or, in fact, any management options for acidic lakes, it is important to establish management objectives that are reasonable expectations considering the resource as a whole. The success of liming depends, in part, on use of appropriate liming materials at appropriate applications rates. Several environmental factors, including high seasonal or annual flushing rates and continual acidic inputs to the lake, can limit the potential for successful liming. Similarly, various other environmental conditions, in addition to high acidities, can restrict survival, growth, and reproduction of fish populations. Such conditions can include overly warm or cold water temperatures, low dissolved oxygen concentrations, the presence of other toxic materials, low basic productivities for food organisms, and limited access to or availability of appropriate spawning or rearing habitats. When limitations on populations caused by high acidities are removed, habitat limitations caused by other environmental conditions may become increasingly apparent and important.

Overall management goals for a limed lake, therefore, should be established based on available knowledge of the historical fisheries in the lake, on how the dynamics of any existing fish populations were limited by natural conditions, and on how conditions now present in the lake may additionally limit the potential success of any fishery after liming. The following sections discuss many of these considerations and outline the understanding needed for defining appropriate management objectives in limed lakes.

EVALUATING THE SUITABILITY OF LAKES FOR LIMING

Before liming a lake to improve its habitat for fish, several factors should be evaluated to determine whether liming could actually benefit the habitat, and whether liming can potentially aid in meeting fishery management goals. Applying the following lake selection criteria can help to prevent the treatment of lakes that will not actually benefit from liming because (1) habitat conditions other than those related to acidity may be limiting the fisheries; (2) the natural dynamics in the lake will prevent liming from being an effective solution to the lake's acidity problem; or (3) liming may adversely impact a preexisting native community in a naturally acidic lake.

The eight lake selection criteria listed below are based on those presented by Saunders et al. (1985), Brown and Goodyear (1987), and Living Lakes, Inc. (LLI 1987). These criteria were slightly modified for presentation here to permit a more general use for routine, operational limings of lakes and ponds

managed for brook trout. These criteria also generally conform to those issued by the NYSDEC (1988) for selection of candidate liming waters. Should the lake not meet any one of these eight criteria, there is serious doubt whether liming will substantially improve the lake habitat for fish or other aquatic life. (It should be noted that selection of the ELS lakes was based on alternate selection criteria, as described in a later section. The ELS results, consequently, helped to affirm the validity of these eight criteria.)

1. There should be reason to believe that the lake is being negatively impacted by high acidities. For example, data collected within the last 5 years should indicate that the lake had pH values less than 6.0 or an alkalinity values less than 10 μeq/l (0.5 mg/l) either (1) frequently, (2) for two or more weeks per year, or (3) over seasonal times critical to sensitive life stages for important biota; or summer surface pH must be less than 5.7 or ANC must be 20 μeq/l (1 mg/l) or less.

2. The lake should have either (1) an existing fish population (naturally reproducing, put-and-take, or put-grow-and-take fishery); or (2) historical records indicating that such a population has previously existed in the lake.

3. The lake should have a water retention time of at least 0.5 year.

4. The surface area of the lake should be greater than about 2 hectares (5 acres) and its maximum depth should be greater than about 3 meters (10 feet).

5. Suitable habitat (e.g., spawning sites, nursery areas, cover, dissolved oxygen, and temperature regimes) to meet management objectives should exist in the lake after liming for successful establishment or reestablishment of the fish species of interest. For example, maximum summer temperatures in excess of about 23°C (74°F) can substantially reduce the ability of brook trout to survive other environmental stresses.

6. Fish populations inhabiting the lake following liming should not be under stress due to nutrient enrichment or other impacts from point or non-point source pollution.

7. The concentrations of selected metals in the lake should not be abnormally high (e.g., indicating possible impacts due to deposition of smelter emissions), but should be typical of other natural lakes in the region with similar hydrologic characteristics and pH values.

8. Historical and recent records should indicate that the lake is not dominated by natural acidification (e.g., acid bogs or other waters containing high concentrations of organic acids) in which naturally acidophilic ("acid loving") communities have become established. Such lakes often lack significant inlets or outlets, have greater than 25% of the lake basin covered with floating _Sphagnum_ mats, have an apparent color of greater than 75 platinum-cobalt units, and/or have dissolved organic carbon (DOC) concentrations of greater than 4.5 mg/l. (Specialized aquatic

communities that have adapted to life in naturally acidic lakes can be adversely impacted by liming.)

Finally, the direct and indirect costs for the materials, manpower, and equipment associated with an operational liming program can represent a substantial investment. Of course, the actual cost of liming a lake depends on the technology, neutralizing material (including material transport), and dosage used. Recent data from the NYSDEC indicate that costs for lake liming ranges from about $119/ha ($48/acre) for easily accessed ponds to $272/ha ($110/acre) for more remote ponds that are limed using a helicopter (NYSDEC 1988). While use of volunteer labor can further decrease the minimum costs of liming, the NYSDEC (1988) indicates that even at the higher costs for remote ponds, a favorable benefit/cost ratio can exist for liming relative to angler usage, angler expenditures, and overall environmental improvements. Nevertheless, prior to any liming operation, it is important to consider whether the resources to be protected are of adequate economic, cultural, or ecological importance in the region or to specific users to warrant the costs associated with liming. Because lake liming only represents a temporary solution to acidic lake conditions, the decision to lime must be made with the understanding that the lake will very likely have to be relimed repeatedly in the future to maintain favorable conditions for fish.

SELECTING THE LIMING MATERIALS

A diversity of basic materials can be and have been used to reduce acidity levels in natural waters and to enhance fish production (Fraser and Britt 1982). Available liming materials include limestone, quicklime, slaked lime, basic slag, blast-furnace slag, basic flyash, stack dust, and soda ash (Boyd 1982, Flick et al. 1982). Studies by Grahn and Hultberg (1975), Edzwald and DePinto (1978), and Davison and House (1988) show the distinctive chemical neutralization dynamics, and the advantages or disadvantages associated with each of these materials.

When selecting the materials to apply in neutralizing acidic waters, consideration should be given to the concentrations in the water for three chemical variables that most directly affect the survival and growth of fish in acid waters: high hydrogen ion concentrations (i.e., high acidities), high aluminum concentrations, and low calcium concentrations. Excess hydrogen ions present under acidic conditions react with soil materials to release aluminum. As discussed in a later section, elevated hydrogen ion and aluminum ion concentrations interact to impact brook trout, but these impacts can be mitigated to some extent by elevated calcium levels.

General practice has shown limestone, which is primarily $CaCO_3$, to be the most useful material for treating acidic surface waters (LLI 1987). It is, therefore, the material primarily discussed in the remaining sections of this report. Limestone can produce the desired level of neutralization in lakes; has no adverse chemical effects on fish, even if applied in a moderately excessive dosage; is cost effective; dissolves relatively readily in water; can at least partly dissolve and enter water columns from lake bottoms; is safe to handle; and is generally free of chemical contaminants that potentially could

fertilize or otherwise contaminate treated waters. Limestone used for lake treatment should contain at least 70% $CaCO_3$, and less than 5% $MgCO_3$, 5% organic material, 0.1% phosphate, 1% aluminum, 1000 mg/kg manganese, 100 mg/kg lead, and 0.5 mg/kg mercury (LLI 1987). These analyses should be provided by the vendor of the limestone.

DETERMINING THE APPROPRIATE STRATEGY FOR LIMING

Neutralizing the Water Column

The dose of material required to treat acidic lake waters depends primarily on the neutralizing chemical used, its purity, the mean diameter of its particles, the chemistry of the treated water, and the volume of the water to be treated (Fraser et al. 1985). Other factors that can be important in determining appropriate applications for liming include (1) the flushing rates for the lake; (2) the amount of basic material applied to sediments necessary to permit subsequent dissolution of this material into the water column to provide a residual neutralization of ensuing acid inputs; and (3) possible application of limestone to the watershed to neutralize runoff water.

Agricultural limestone (ag-lime) has often been used to neutralize acidic lakes because it is relatively inexpensive and commonly available. Finer grades of limestone, however, are more effective treatment agents. Since ag-lime has a relatively coarse average particle size of 0.2 mm (0.001 inch) or greater, the area on the particles exposed to the water is relatively small and the particle dissolves relatively slowly. For example, only about 10 to 15% of the ag-lime applied to pH 5.5 water will dissolve as it travels through the water column, leaving 85 to 90% on the bottom, where some may dissolve into the overlaying water; but the neutralizing ability of limestone in bottom sediments is minimal after 1 to 2 years (Fraser et al. 1985, Gloss et al. 1988, LLI 1988).

Maximum dissolution efficiencies are obtained using slurries of fine limestone dissolved in water. Limestone 10- to 20-times finer than ag-lime normally has dissolution efficiencies of 40 to 60%; and these materials leave a smaller, but potentially more useful limestone dose on the sediments (LLI 1988). Overall, use of finer grades of limestone may be the most cost-effective, considering the smaller amount of limestone needed and less labor required to complete the treatments.

Where access permits, acidic lakes can be effectively treated with slurries of fine limestone applied using boats or barges. This technique involves the thorough mixing of dry-powdered limestone with lake water in an on-board tank. When the resulting slurry is pumped over the bow into the propeller wash of the boat motor, it more thoroughly mixes with lake waters. Often, though, the most cost effective technique to treat more remote lakes is through aerial applications using helicopters. Fraser et al. (1985) and LLI (1987) present detailed considerations of treatment technique alternatives.

A typical goal when liming acidic lakes is to establish a water chemistry having a pH greater than 6.5, an ANC of greater than 100 μeq/l, and Ca concentrations of greater than 5 to 10 mg/l for the longest time with the minimum dose

of base material. Such pH and ANC levels are presumed to represent natural pre-acidified levels or otherwise non-toxic conditions in the treated lake. In addition, these levels generally provide a buffer against rapid reacidification.

As indicated in the opening paragraph of this section, computation of adequate dosing rates for applying limestone to acid lakes can depend on many variables. One of the more simple approaches for estimating the needed dose of limestone is to titrate samples of water and sediment from the lake with samples of the material that will be applied during treatment of the lake (DePinto and Young 1985). The goal is to determine the amount of limestone necessary to obtain an alkalinity of equal to or greater than 200 μeq/l within 24 hours. This dosage can then be extrapolated to estimate the mass of limestone necessary to treat the whole lake by using the volume of the lake. A bathymetric survey is needed to determine the volume of the lake.

Alternative and more extensive procedures are available to determine appropriate dosing rates. First, it is easiest, but potentially most costly, to hire experts experienced with lake liming to calculate the correct dosages and manage the lake treatment activities. Second, general information and guidelines on determining limestone application rates for smaller fish culture ponds is provided in the text by Boyd (1982).

Third, a computer program, DeAcid, can be used to estimate appropriate dosing rates (Saunders et al. 1985). Use of DeAcid or some similar program is recommended by the NYSDEC (1988). The computational approaches used in this program are summarized by Sverdrup (1983, 1984) and Gloss et al. (1988). In actual use, this interactive program requests that the user supply information on the lake's size, flushing rate, hydrologic regime, water quality (pH, ANC, calcium content, dissolved inorganic carbon, etc.), physical and chemical properties of the limestone to be used, and final water quality goals of the treatment program. DeAcid then calculates the appropriate limestone application rate for the lake. While the application rate projections made by this program have been found to be generally useful, experience has shown that amounts of limestone needed to adequately treat some coastal seepage lakes are overestimated (Adams and Brocksen 1988). This apparent bias in the model should have little impact on its ability to calculate appropriate dosages for lakes in the Adirondack region.

Treating Lake Sediments

For lakes having slow water exchange rates, the principal concern is to neutralize the acidity of the water column. In such systems sediment dosing is fairly ineffective because the limestone applied to the sediments deactivates before lake reacidification can consume its neutralizing potential. This deactivation occurs as metal oxides accumulate on the calcite particles and as these particles become covered with additional sediment. In rapidly flushing systems (<1 yr), however, a sediment dose of 0.3 to 0.7 ton/ha can help prolong the neutralization provided by a single liming treatment (LLI 1988).

Sediment dosing with limestone is needed if the sediment pH is less than 5.5 or if the lake flushing rate is less than one year. Larger doses of lime applied to the water column in more rapidly flushing lakes do not prolong the

effectiveness of liming. A larger dose only leads to a rapid flushing loss for more of the treatment materials and very little change in the reacidification rate for the lake. Both the computer program DeAcid and the text by Boyd (1982) provide guidance on determining appropriate sediment doses. Technical considerations on the dissolution of calcite applied to sediments are presented by DePinto et al. (1987), Scheffe et al. (1986a), and Sverdrup et al. (1984).

Treating the Surrounding Watersheds

The present state-of-the-knowledge concerning watershed liming was recently reviewed by Brown (1988). For lakes with water retention times exceeding one year, he concluded that this approach on a per-year basis can be up to six-times more costly than direct lake dosing; but with more rapidly flushing systems, the costs may be more similar. Those systems potentially most benefited by watershed liming include (1) acidic lakes with water exchanges of less than one-half year, and (2) acidic streams containing fish spawning areas. Overall, watershed liming apparently can satisfactorily reduce potentially toxic aluminum concentrations in surface waters and reduce the severity of acid runoff events. But, Brown also noted that the principal adverse impact of watershed liming is that this technique can adversely affect the growth and survival of some acid-loving aquatic and terrestrial plants.

Reacidification and Reliming Thresholds

Liming has only a temporary neutralizing effect on the chemistry of a lake. As acidic runoff from the surrounding watershed dilutes the ANC of the dosed limestone, reacidification occurs. The rate of reacidification depends on the degree that limestone dissolves in the water column, the rate at which limestone buffered water is flushed from the lake, the rate limestone dissolves from the sediments into the water column subsequent to liming, and the extent to which acidic waters continue to enter the lake.

During the ELS project, rates of lake reacidification varied with different hydrologic and morphometric features among each of the ten dimictic lakes (lakes that mix vertically in the spring and fall) in the Adirondacks (Gloss et al. 1988). This study revealed that the rate at which calcium was removed from the water column was significantly correlated ($R^2 = 0.96$) with the ratio of watershed area to lake volume (W:V). The regression relationship derived for the percentage decrease in calcium concentration during the first year following liming of was

$$\% \text{ decrease in } [Ca] = -2.304 + (13.177 \times W:V)$$

Other generally more complex approaches to estimate reacidification rates have been presented by DePinto et al. (1987), Scheffe et al. (1986b), Sverdrup (1986), Sverdrup and Warfvinge (1985), and Wright (1985). All of these approaches, however, can be problematic because reacidification projections depend on a reasonably accurate knowledge of flushing rates, and/or acid loading rates to the lake. Generally, neither value is known but rather is estimated for most lakes included in typical fisheries management liming programs.

Importantly, any model projection of lake reacidification must be verified with monitoring of the lake to determine the actual rate of reacidification. Previous liming/reacidification experience on a lake provides the best indication of probable future liming/reacidification responses for the lake. Typically, under a fisheries management/liming program, reliming should be scheduled whenever the pH drops below 6.0, or the ANC below 50 to 100 μeq/l (< 2.5 to 5.0 mg/l as $CaCO_3$). Within the context of a liming program for fisheries management, monitoring results relative to these water quality criteria must be the ultimate determinate of when reliming will be necessary to maintain environmental conditions acceptable for perpetuation of the resident fish populations.

Under maintenance liming programs when fish are present, care must be taken to minimize increases in acidity and metal concentrations prior to reliming. As discussed earlier, the solubility of most metals increases as acidity increases, and much of the adverse impacts to fish associated with surface water acidification is a consequence of toxicity due to elevated aluminum concentrations. With liming, there is also a potential that a rapid precipitation of dissolved metals may additionally stress resident fish. Grahn (1980) suggested that high aluminum concentrations in surface water flocculated when the acidity naturally increased rapidly, and that this flocculated aluminum clogged fish gills, causing their mortality by suffocation. While similar aluminum affects to fish during acid reductions were not seen in the ELS project (Schofield et al. 1986) or in the Lake Acidification Mitigation Project (Gloss et al. 1987), Dickson (1983) reported that aluminum toxicity caused high mortality of stocked rainbow trout shortly following liming in Sweden. Minimizing the acidity increase allowed prior to reliming can limit the potential stress to resident fish that may accompany both acid and metal increases.

Finally, reliming may also help reduce possible accumulations of metals in fish flesh from acidic waters. Sloan and Schofield (1983) reported levels of mercury in fish to be higher in low-ANC lakes than in higher-ANC lakes in the Adirondacks. Three primary sources of mercury in low-ANC waters are (1) weathering of minerals; (2) atmospheric deposition of naturally occurring mercury; and (3) atmospheric deposition of mercury from man-caused sources (Brosset 1981, 1987). Several studies show that mercury concentrations in fish tend to increase as water acidity increases (e.g., Richman et al. 1988, Wiener 1988). A quantified relationship between lake acidification and mercury concentrations in fish, however, does not currently exist; high mercury concentrations can be found in fish from either acid or circumneutral waters (Phillips et al. 1987). Thus, the risk to humans from possible mercury increases as a consequence of lake acidification remains unknown.

ESTABLISHING FISHERY MANAGEMENT OBJECTIVES FOR LIMED LAKES

For most limed lakes the fisheries management objective will be to maintain a fishery as similar as possible to the historical fishery found in the lake. When no existing fishery is present, a useful starting place in defining fishery management objectives for a lake to be limed is to determine whether fish populations historically inhabited the lake, what fish species have inhabited

the lake, and whether these species maintained self-sustaining populations or whether they were maintained by stocking. Such information is often available from files in local offices of state fisheries agencies. For some lakes, however, the only source of historical fisheries information may be old newspaper clippings, lake association newsletters and memoranda, or even anecdotal accounts from the area's older residents.

For the Adirondack region, the vast majority of lakes that historically contained fish were inhabited by populations of brook trout; this is also the fish species that apparently has had the most extensive impact as a consequence of acidification in this region (Haines and Baker 1986, Schofield 1982). Therefore, brook trout is the fish species of primary concern for maintaining or reestablishing in Adirondack lakes following liming.

Often, the ultimate goal for a managed fishery is that the population will naturally maintain adequate reproduction rates yielding enough fish to sustain satisfactory harvest success for the realized fishing pressure. Unfortunately, many lakes lack sufficient spawning or rearing habitats for brook trout to obtain this goal. Therefore, it often is necessary to augment, or even totally maintain a brook trout fishery by stocking. Stocking is also necessary where mitigative liming is conducted to restore fisheries in lakes where historical fish populations were reduced or eliminated due to acidification.

General Habitat and Life History Relationships for Brook Trout

Optimal lake habitat for brook trout is typically characterized as having cold, clear, oligotrophic water. Because brook trout appear to be opportunistic sight feeders, they are susceptible to moderate turbidity levels that can limit their abilities to locate food (Raleigh 1982).

Most brook trout lakes exceed about 4.5 m (15 feet) in depth, or have adequate spring or tributary flows to provide cool, oxygenated water throughout the year. Brook trout fry require shallow, low velocity waters with 10- to 40-cm (4- to 16-inch) diameter rubble or aquatic vegetation for cover. Older brook trout also appear to prefer rubble substrate, aquatic vegetation, and submerged brush as cover (Raleigh 1982).

Water temperatures are the primary factor limiting the distribution of brook trout. This species is rarely found naturally in waters where surface-water temperatures exceed 20°C (68°F) for extended periods (Raleigh 1982). Brook trout also generally require dissolved oxygen concentrations of greater than 5-6 mg/l when water temperatures exceed 15°C (59°F).

In both lakes and streams, the fall-spawning brook trout appear to require silt-free spawning sites, primarily where ground waters upwell through gravel and rubble substrates (Gunn 1986, Webster and Eiriksdottir 1976). Where lakes lack submerged springs for spawning, successful brook trout recruitment to the lake can occur in inlet or outlet streams containing suitable spawning habitat.

Brook trout growth rates depend on many environmental conditions, including the productivity of their food organisms, their own population densities, competition with other species, and fisheries management practices, including

allowed harvest rates and sizes (Raleigh 1982). In some lakes male brook trout can reach sexual maturity during their first year, but most males generally become sexually mature during their second year and females in their third. Most brook trout have a maximum life span of 3 to 4 years.

Brook trout populations in eastern North America do not compete well with other fish species, doing best in a single species fishery. If competitors such as minnows, suckers, yellow perch, carp, and rainbow trout are present, brook trout survival and/or growth rates are often low. Also, brook trout populations generally are highly susceptible to angling and may be easily fished out of lakes.

Relationship of Brook Trout to Acidic Waters

Important from the standpoint of acidic lakes, brook trout have relatively high tolerances to low pH waters (Baker 1984, Mount and Marcus 1989). Their survival in low pH waters depends on the dissolved concentrations of inorganic monomeric aluminum (primarily the Al^{3+}, $Al(OH)_n^{x+}$, and AlF_n^{x+} ions, the aluminum complexes that are most toxic to fish), on the presence of refuges having higher pH waters, and on the availability of good spawning sites. When inorganic monomeric aluminum concentrations are low, such as in naturally acidic brown water lakes or streams, adult brook trout can survive over extended periods of time at pH levels as low as 4.8. Reproducing brook trout populations inhabit some waters having pH values as low as 5.0, but most brook trout populations occur where pH values remain above 5.5 (Marcus et al. 1986).

Losses of brook trout from acidic waters appear to be caused primarily by elevated concentrations of both hydrogen and aluminum ions interacting to produce ion imbalance and respiratory stress in the fish, leading to death (Booth et al. 1988, Wood et al. 1988a). It is doubtful that reproductive failure in adult brook trout significantly contributes to the elimination of most brook trout populations (Mount et al. 1988).

Freshly fertilized eggs appear to be the life stage most sensitive to the effects of acidity alone; in contrast, elevated aluminum concentrations alone are most toxic to fry, juvenile, and adult fish (Mount and Marcus 1989). Effects of acidity alone become apparent in brook trout at pH levels below 5.2; whereas concentrations of inorganic monomeric aluminum greater than about 0.1 to 0.2 mg/l (depending on ambient water pH and calcium concentration) can affect the survival of this species in low calcium water (Mount et al. 1988). Impacts on brook trout due to adverse water quality conditions were documented in the ELS lakes prior to liming with in situ bioassays using caged brook trout fingerlings (Schofield et al. 1986).

The adverse effects caused by both elevated acidity and aluminum levels can be lessened as water calcium concentrations are increased above 0.5 to 1.0 mg/l (Booth et al. 1988, Wood et al. 1988a, Mount et al. 1988). In fact, the importance of increased calcium concentrations in the water continues to be beneficial for many species at least until water concentrations exceed 4 mg/l, and may extend to above 8 mg/l for brook trout (Marcus et al. 1986, Mount and Marcus 1989, Mount et al. 1988). Therefore, when acidic water concentrations of calcium are less than 4 mg/l, the goal of liming should be not only to reduce

the water acidity and aluminum levels, but also to increase the water calcium concentrations.

Influences of Lake Hydrologic Patterns on Responses by Brook Trout

Relatively few actual losses of fish populations have been directly observed as a result of surface-water acidification. This is at least partly due to the difficulty in directly observing recruitment failures and other such chronic impacts on fish populations in nature. Those fish kills that actually have been directly observed in lakes and streams have been primarily associated with episodic rainfall or snowmelt events (Baker 1984). Such episodic events, which can rapidly wash relatively high concentrations of acutely toxic acids and dissolved aluminum into lakes and streams, in fact, may be the most common cause of fish loss from acidifying surface-waters (Baker 1984, Gunn 1986). Aquatic organisms have generally low physiological abilities to adapt to the rapid changes in environmental chemistries that can accompany episodic events.

Since brook trout apparently spawn almost exclusively in gravel and rubble containing upwelling waters (Webster and Eiriksdottir 1976, Gunn 1986), these upwellings can protect the hatching fry until their emergence from the gravel into the water column. But the emergence of brook trout into the water column may coincide with spring snowmelt. Thus, emerging brook trout fry can be exposed to stressful water qualities and die when snowmelt waters contain acutely toxic acid and/or aluminum concentrations. This mechanism may be, in fact, the principal cause of acidification related brook trout mortality in streams (Gunn 1986).

In lakes, however, the very cold snowmelt water (ca. 0°C, 32°F) can be less dense than resident lake waters. At such times, the relatively colder, lighter snowmelt water can flow over layers of warmer, heavier lake water. This, thereby, limits exposure of any emerging brook trout fry to the relatively brief time necessary for the fry to travel through the acidic layer and reach the water surface to fill their air sacs.

When acidic snowmelt waters overflow deeper lake layers, resident brook trout may avoid the potentially toxic meltwater layer by finding refuge in the deeper, less acidic layers of the lake. When non-toxic waters are available for refuge, brook trout are able to and do, in fact, avoid waters having potentially toxic acid and/or aluminum concentrations (Gunn 1986, Gunn and Noakes 1986, Johnson and Webster 1977). Other refuge areas potentially available to brook trout populations in acidic lakes include (1) high volume inflows from submerged springs, (2) inflows from tributary streams that provide non-toxic waters, and (3) out migration to these streams. These environments can provide important refugia for brook trout in limed lakes during times of episodic inflows by potentially toxic snowmelt or storm-event waters, and during critical periods reacidification following liming.

OVERVIEW OF THE EXTENSIVE LIMING STUDY (ELS)

GENERAL CHARACTERISTICS AND SELECTION CRITERIA FOR THE ELS LAKES

General physical characteristics of the lakes included in the ELS study are shown in Table 1. These ten lakes were selected from among twenty-two candidate lakes, which were first chosen using unpublished lake survey information provided by the NYSDEC (Schofield et al. 1986). Criteria used to select the ELS lakes for final study included (1) a surface area of <10 ha (<25 acres); (2) a range of hydrologic conditions necessary to assess re-acidification rates; (3) temperature and oxygen regimes suitable for brook trout; and (4) remote locations to minimize effects of angling in confounding fish population responses to liming. (Again, the selection criteria used for the ELS lakes differed from those presented on pages 5 and 6.) Prior to liming, the ten ELS study lakes were chronically acid (pH < 5.0) and devoid of fish. Low pH and elevated aluminum concentration were presumed to be the cause of their fishless condition.

CHEMICAL CHARACTERISTICS OF THE ELS LAKES

Chemical characteristics of the lakes were evaluated during the summer and early fall of 1983 and 1984, prior to the final selection of the ten study lakes. Average chemical conditions in the ten ELS lakes in the weeks before liming are summarized in Table 2. The selected lakes were divided into two groups of five lakes each. The first group was limed and stocked with brook trout in the fall of 1983, and the second group was similarly treated in the fall of 1984. Information on actual treatment applications for each lake is shown in Table 3. Average chemical conditions measured during the period following the fall liming through April 30 the next spring are summarized in Table 4.

COMPARISON OF THE ELS LAKES WITH OTHER ADIRONDACK REGION LAKES

General morphometric and chemical characteristics of all lakes surveyed by the Adirondack Lake Survey Corporation (Kretser et al. 1989) in the Adirondack region are summarized in Table 5. In comparison to the mean characteristics of these 1469 Adirondack lakes, the ELS lakes averaged smaller surface areas and volumes but greater mean and maximum depths, slower lake flushing rates, greater acidities, and lower calcium concentrations. Examining unpublished data for these 1469 ALSC lakes in greater detail reveals

- o 3 lakes had a pH of less than 4.0;
- o 24% (351 lakes) had a pH of less than 5.0;

Table 1. Morphometric characteristics of the ELS lakes (Gloss et al. 1988, Schofield et al. 1986).

Lake	Surface Area (ha)	Lake Volume (m^3)	Watershed Area (ha)	Mean Depth (m)	Maximum Depth (m)	Retention Time (months)
<u>Group I Lakes</u>						
Big Chief	1.2	53,020	19.5	4.4	11.0	4.6
Highrock	4.0	140,163	16.7	3.5	8.2	12.3
Little Rock	4.1	55,105	179.5	1.4	2.4	0.5
Mountain	6.0	278,743	49.7	4.7	8.5	9.0
Trout	3.7	46,016	67.5	1.3	7.3	1.2
<u>Group II Lakes</u>						
Barto	5.5	156,313	72.5	2.9	7.3	3.1
Indigo	5.7	207,750	21.0	3.7	6.0	14.2
Jones	5.3	336,507	16.8	6.4	14.7	27.9
Pocket	1.2	34,718	23.6	2.9	11.6	2.5
Silver Dollar	0.5	20,596	9.8	4.1	8.5	3.6
<u>Means</u>	3.7	132,893	47.7	3.5	8.6	7.9

Table 2. Means, standard deviations, and ranges of the pre-liming water qualities for the ten ELS study lakes, includes dates of the pre-liming samples.

Lake		O_2 mg/l	Fe ug/l	Field pH	Lab pH	ANC ueq/l	Ca mg/l	Al_a[1] ug/l	Al_t[2] ug/l	Al_{to}[3] ug/l
<u>Group I Lakes</u>										
Big Chief	Mean		8		4.8	0.7	2.1	279	316	
9/16/83-	Std. Dev.		8		0.1	3.4	0.9			
9/23/83	Max.		16		4.8	4.0	3.3			
	Min.		0		4.7	-4.0	1.5			
Highrock	Mean	9.5	91	5.1		-3.0	1.8	183	185	
10/11/83-	Std. Dev.	0.4	0	0.0			0.2			
10/14/83	Max.	10.0	91	5.2			1.9			
	Min.	9.0	91	5.1			1.5			
Little Rock	Mean	5.3	800	4.7	4.8	3.6	1.0	122	304	
9/6/83-	Std. Dev.	0.3	532	0.0	0.0	8.9	0.1		104	
9/23/83	Max.	5.6	1332	4.8	4.9	16.0	1.0		408	
	Min.	5.0	268	4.7	4.8	-9.0	0.9		199	
Mountain	Mean	7.3	648	4.7	4.7	-5.8	1.4	370	1025	
8/29/83-	Std. Dev.	0.1	620	0.1	0.1	4.0	0.1	45	638	
10/12/83	Max.	7.4	1268	4.8	4.8	0.0	1.6	415	1662	
	Min.	7.2	27	4.7	4.6	-10.0	1.4	325	387	
Trout	Mean	6.8		4.6	4.8	-3.0	1.8			
9/14/83	Std. Dev.	0.2		0.1	0.1	3.6	0.0			
	Max.	7.0		4.7	4.9	2.0	1.8			
	Min.	6.5		4.4	4.7	-6.0	1.8			
<u>Group II Lakes</u>										
Barto	Mean	7.9	82	4.6	4.7	-10.1	0.8	300	413	70
8/29/84-	Std. Dev.	0.4	24	0.0	0.0	5.9	0.1	24	13	21
9/21/84	Max.	8.8	108	4.7	4.8	0.0	1.1	326	434	104
	Min.	7.6	31	4.5	4.6	-20.0	0.6	263	394	43
Indigo	Mean	8.1	257	4.9	4.9	0.5	1.1	27	110	38
8/6/84-	Std. Dev.	0.5	170	0.1	0.1	3.8	0.0	32	6	11
10/10/84	Max.	8.8	622	5.2	5.0	6.0	1.2	78	123	61
	Min.	7.0	75	4.8	4.8	-7.0	1.1	0	102	24
Jones	Mean	8.6	55	4.9	5.0	-0.8	1.2	86	158	44
8/6/84-	Std. Dev.	1.3	25	0.1	0.1	2.8	0.1	46	21	18
10/1/84	Max.	11.2	89	5.3	5.2	4.0	1.4	132	201	85
	Min.	7.0	14	4.8	4.9	-4.0	1.1	0	138	27
Pocket	Mean	7.1	372	4.5	4.3	-35.3	0.7	420	550	221
7/3/84-	Std. Dev.	0.8	522	0.6	0.1	15.9	0.1	258	125	111
9/17/84	Max.	8.2	1747	6.0	4.6	1.0	0.9	938	850	483
	Min.	6.0	105	4.2	4.3	-50.0	0.6	177	461	142

Table 2. Continued.

Lake		O_2 mg/l	Fe ug/l	Field pH	Lab pH	ANC ueq/l	Ca mg/l	Al_a[1] ug/l	Al_t[2] ug/l	Al_{to}[3] ug/l
Silver Dollar	Mean	6.8	274	4.2	4.3	-40.9	0.7	356	473	240
7/4/84-	Std. Dev.	0.5	238	0.1	0.0	13.8	0.1	228	131	106
9/15/84	Max.	7.4	803	4.4	4.4	-10.0	0.9	778	759	453
	Min.	6.0	96	4.1	4.2	-59.0	0.6	126	384	166

[1] Labile monomeric aluminum (includes the most toxic fraction).
[2] Total aluminum.
[3] Total uncharged or non-labile aluminum (an operational fraction determined after removal of charged Al species by cation exchange).

Table 3. Liming application dates and dose rates for the ELS lakes (Schofield et al. 1986).

Lake	Application dates	Total Dose Rate (g/m^3)	Limestone Applied (metric tons)
Group I Lakes			
Big Chief	9/27-10/16/83	85.6	4.54
Highrock	10/31-11/ 9/83	51.8	7.26
Little Rock	9/28-10/ 4/83	82.4	4.54
Mountain	10/14-10/22/83	43.2	12.02
Trout	10/17-10/22/83	108.5	4.99
Group II Lakes			
Barto	10/ 3-10/19/84	83.9	13.11
Indigo	10/13-10/17/84	44.8	9.30
Jones	10/ 4-10/12/84	52.6	17.69
Pocket	9/18- 9/22/84	183.3	6.35
Silver Dollar	9/24/84	132.3	2.72

Table 4. Means, standard deviations, and ranges of the post-liming water qualities for the ten ELS study lakes, includes dates of the post-liming samples.

Lake		O_2 mg/l	Fe ug/l	Field pH	Lab pH	ANC ueq/l	Ca mg/l	Al_a[1] ug/l	Al_t[2] ug/l	Al_{to}[3] ug/l
Group I Lakes										
Big Chief	Mean	7.5	162	5.9	6.8	113	4.4	276	488	
10/17/83-	Std. Dev.	1.3	29	0.5	0.4	77	1.5	145	128	
4/26/84	Max.	10.0	218	7.0	7.3	254	7.2	624	821	
	Min.	5.2	101	4.8	6.1	-18	2.1	84	356	
Highrock	Mean	8.2	142	6.2	6.6	132	5.1	230	359	
11/2/83-	Std. Dev.	2.9	75	0.5	0.8	103	1.9	200	158	
4/26/84	Max.	12.8	271	6.9	7.4	442	11.0	900	797	
	Min.	4.2	70	4.6	4.6	-15	1.3	8	174	
Little Rock	Mean	10.5	504	5.0	6.1	11	2.2	418	568	
10/5/83-	Std. Dev.	2.7	345	0.8	1.1	84	1.0	241	148	
3/29/84	Max.	13.2	1082	6.5	7.3	157	4.3	722	792	
	Min.	6.0	138	3.8	4.6	-149	1.0	12	305	
Mountain	Mean	9.8	26	6.0	6.5	88	4.2	225	407	
10/23/83-	Std. Dev.	1.8	24	0.6	0.8	89	2.0	178	179	
4/26/84	Max.	12.0	123	7.0	7.7	348	10.5	673	765	
	Min.	5.2	0	4.7	4.7	-12	1.6	40	120	
Trout	Mean	7.0	281	6.2	6.8	148	5.3	237	391	
9/28/83-	Std. Dev.	2.5	185	0.8	0.8	119	2.2	146	139	
4/26/84	Max.	12.4	745	7.3	7.6	401	9.7	645	659	
	Min.	4.0	87	4.5	5.0	-34	1.6	48	214	
Group II Lakes										
Barto	Mean	8.3	68	6.0	6.6	111	3.6	184	368	150
10/24/84-	Std. Dev.	2.0	42	0.8	1.0	71	1.4	251	188	75
4/29/85	Max.	11.0	162	6.9	7.5	221	5.8	932	995	335
	Min.	4.2	0	4.5	4.6	-11	1.1	0	194	33
Indigo	Mean	8.2	224	6.1	6.9	116	3.6	63	140	76
10/24/84-	Std. Dev.	2.3	99	0.5	0.7	60	0.8	76	69	51
4/29/85	Max.	12.0	449	6.9	7.5	201	5.0	244	348	206
	Min.	4.8	19	5.0	4.8	-12	2.2	0	58	22
Jones	Mean	9.1	117	6.4	7.1	118	3.8	78	159	103
10/17/84-	Std. Dev.	1.3	66	0.5	0.4	41	0.6	119	73	54
4/29/85	Max.	11.6	261	7.2	7.4	188	4.9	523	386	198
	Min.	7.0	19	5.3	5.7	29	2.6	0	68	25
Pocket	Mean	6.5	295	5.6	6.1	90	4.0	266	561	350
9/25/84-	Std. Dev.	1.7	120	0.9	1.2	91	2.1	244	158	100
4/25/85	Max.	9.6	463	7.0	7.5	209	6.8	769	826	540
	Min.	4.2	112	4.1	4.2	-52	0.9	0	355	193

Table 4. Continued.

Lake		O_2 mg/l	Fe ug/l	Field pH	Lab pH	ANC ueq/l	Ca mg/l	Al_a[1] ug/l	Al_t[2] ug/l	Al_{to}[3] ug/l
Silver Dollar	Mean	6.5	228	5.7	6.4	109	4.0	187	430	304
9/25/84-	Std. Dev.	1.1	73	0.9	1.2	88	1.7	177	67	62
4/25/85	Max.	8.4	380	7.3	7.7	312	8.5	575	547	429
	Min.	5.4	115	4.4	4.5	-18	1.0	0	336	186

[1] Labile monomeric aluminum (includes the most toxic fraction).
[2] Total aluminum.
[3] Total uncharged or non-labile aluminum (an operational fraction determined after removal of charged Al species by cation exchange).

- o 42% (622 lakes) had a pH of less than 6.0;
- o 17% (251 lakes) had a calcium concentration of less than 1 mg/l;
- o 77% (1137 lakes) had a calcium concentration of less than 4 mg/l;
- o 32% (468 lakes) had a mean depth of greater than 3 m (10 ft);
- o 77% (1133 lakes) had a flushing rate of one-half year or less; and
- o 10% (150 lakes) had a flushing rate of greater than one year.

Figure 1 shows the size distribution for these 1469 surveyed lakes. Morphological and chemical characteristics of the 985 smaller (<10 ha) lakes are presented also in Table 5, and show that these smaller lakes were more similar to the ELS lake. Nearly 50% of the smaller lakes had pH levels less that 6.0, while the pH in 38% of the larger lakes were less than 6.0 (Figure 2). Only 16% of the smaller lakes had flushing rates of greater than twice per year (i.e., lake flushing rates of 6 months or greater), whereas 36% of the larger lakes flushed more than twice per year (Figure 3). Overall, the ELS lakes, except for their often higher flushing rates, represented small, acid-sensitive, drainage lakes in the Adirondack region that could potentially benefit from liming-based fisheries management programs.

CHEMICAL RESPONSES BY ELS LAKES TO LIMING

Agricultural limestone was the base containing material used to lime the ELS lakes. Its principal ingredient is calcium carbonate ($CaCO_3$), which, when dissolved in water having pH levels less than about 4.5, can chemically react directly to neutralize free acidity in the solution:

$$CaCO_3 + 2\ H^+ \text{--->} Ca^{2+} + H_2CO_3.$$

In such reactions, acidity is reduced (i.e., pH increases), but no alkalinity is formed. Carbonic acid (H_2CO_3) also can form through the direct dissolution and reaction of atmospheric CO_2 with water:

$$CO_2 + H_2O \text{--->} H_2CO_3.$$

When the water pH is greater than about 4.5, carbonic acid, which is a weak acid, significantly dissociates to hydrogen (H^+) and bicarbonate (HCO_3^-) ions:

$$H_2CO_3 \text{--->} H^+ + HCO_3^-.$$

Then, when calcium carbonate is added to such solutions containing free carbon dioxide, it reacts to generate bicarbonate alkalinity and calcium:

$$CaCO_3 + H^+ + HCO_3^- \text{--->} Ca^{2+} + 2\ HCO_3^-.$$

Lake liming, thus, normally (1) decreases the waters acidity by consuming H^+ during various chemical reactions; (2) increases its alkalinity, when adequate free CO_2 is present in the water, primarily by increasing HCO_3^- concentrations; and (3) increases its hardness by increasing Ca^+concentrations. Liming may also lead to slight subsequent changes in the dissolved concentrations of phosphorus and nitrogen; but the nature of these changes varies by specific lake (Fraser and Britt 1982, Marcus 1988).

Table 5. Mean morphometric and chemical characteristics for all lakes surveyed and for small lakes surveyed in the Adirondacks by the Adirondack Lake Survey Corporation (ALSC unpublished data).

Lake Type	Number of Lakes	Elevation (m)	Surface Area (ha)	Lake Volume (m^3)	Mean Depth (m)	Maximum Depth (m)	Retention Time (months)	pH	Calcium (mg/l)
<u>All Surveyed Lakes (N = 1469)</u>									
Seepage	204	464	5.6	237,780	2.9	6.6	0.9	5.6	2.4
Drainage	1265	509	18.0	730,545	2.5	6.5	0.3	6.3	3.4
<u>Small (<10 ha) Lakes (N = 985)</u>									
Seepage	179	464	2.4	73,906	2.7	5.9	0.8	5.4	1.7
Drainage	806	516	4.1	88,159	1.9	4.6	0.3*	6.1	3.4

* Based on 800 lakes.

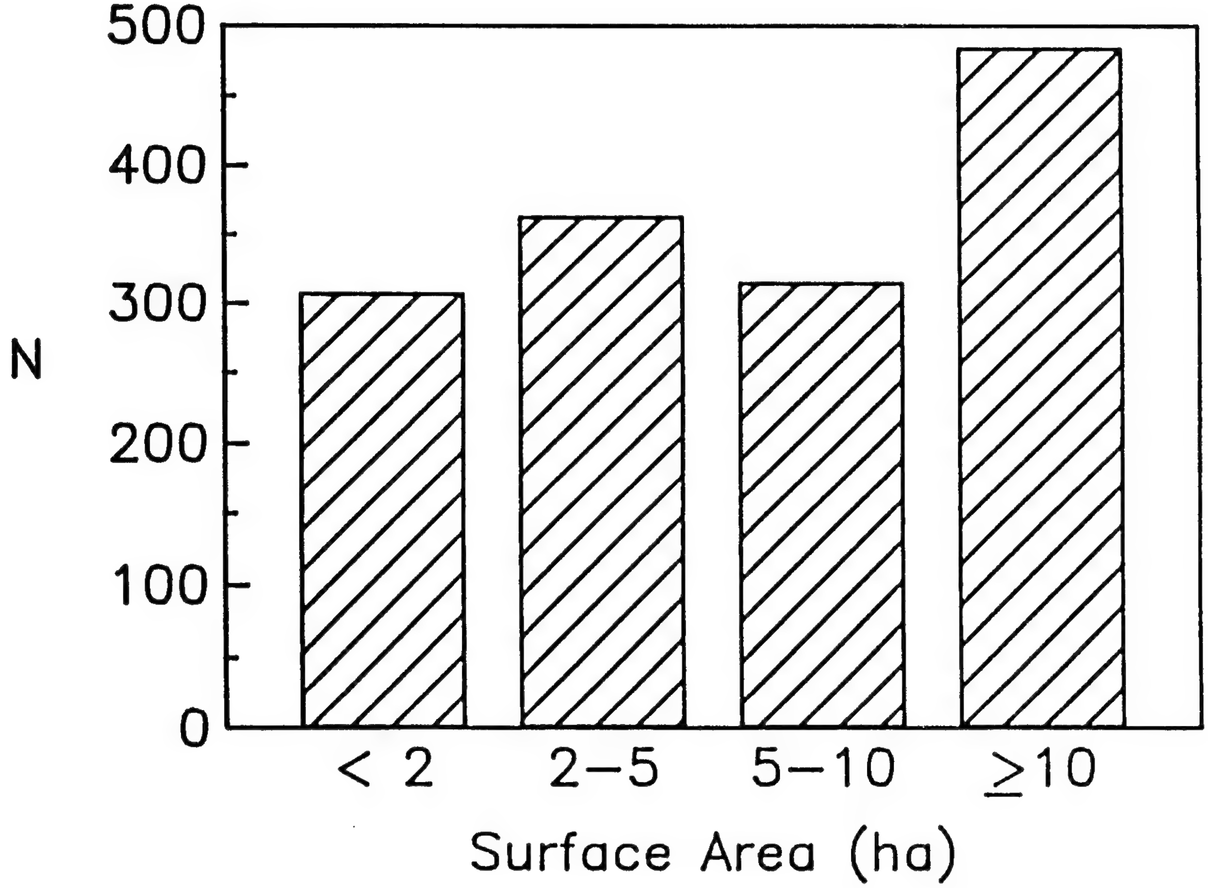

Figure 1. Distribution based on area for 1469 surveyed lakes (Kretser et al. 1989)

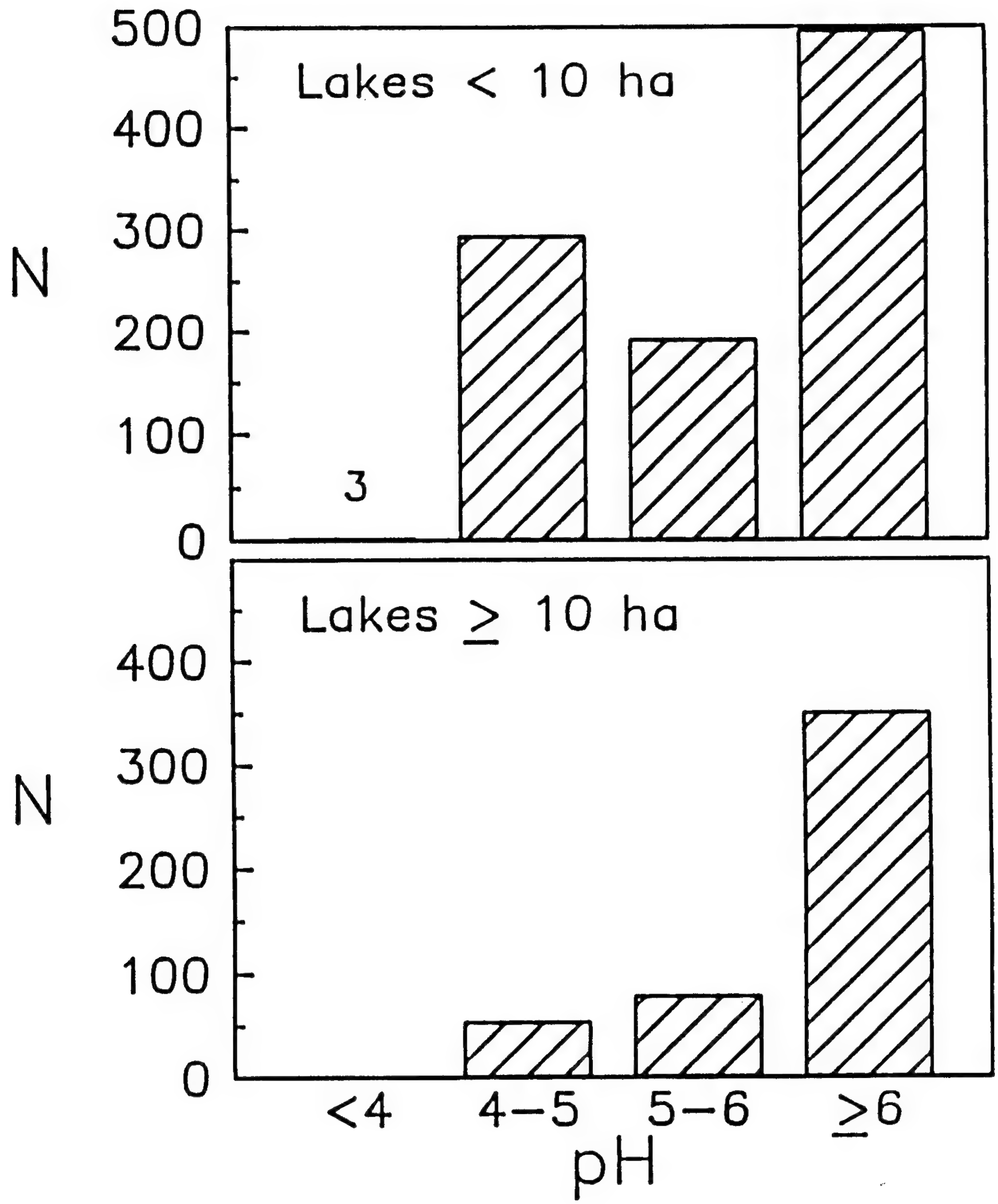

Figure 2. Distributions of air equilibrated pH recorded for 985 smaller and 484 larger surveyed lakes (Kretser et al. 1989).

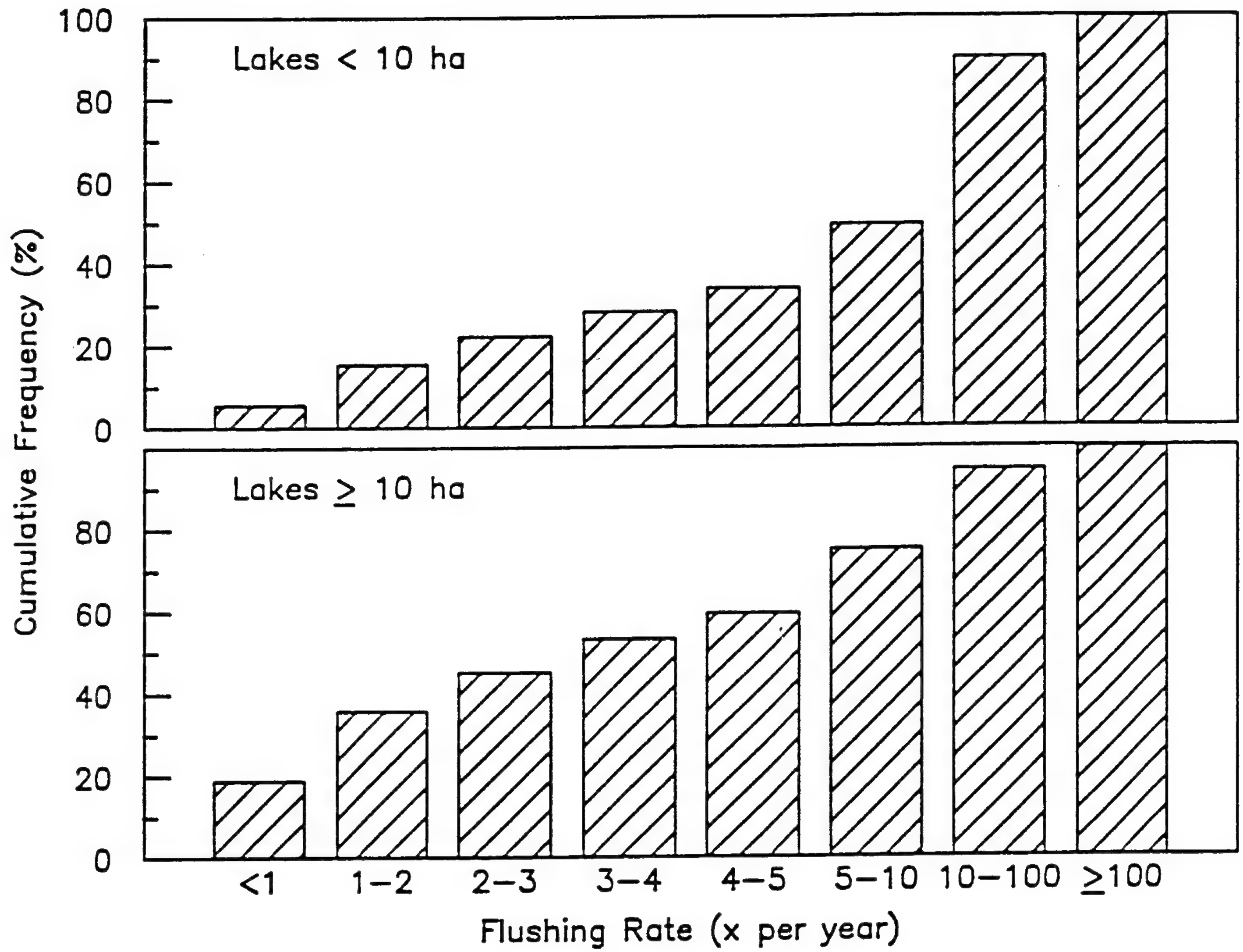

Figure 3. Cumulative frequency distributions of flushing rates (from <1 to ≥100 flushing per year) for 979 smaller and 482 larger surveyed lakes (Kretser et al. 1989).

Liming may additionally cause the transparency of some clear acid lakes to decrease (Wright 1985). This decrease can be caused by increasing growth rates for suspended algae, which increases densities of suspended particles, and/or by increasing rates for other metabolic processes, which, along with photosynthesis can increase production and concentrations of dissolved organic compounds. In humic, colored lakes, however, liming can cause organic colloids to precipitate from solution, leading to increased transparencies (Driscoll et al. 1982).

Changing transparencies in water layers following liming can alter absorption patterns for solar energy through the water column. For example, when the density of particles or dissolved organic matter in a water layer increases, its transparency decreases, absorption of solar energy increases, the heat contained in the waters increases, and its temperature can increase. Then, because deeper waters are in essence shaded, deeper waters can become cooler after liming. Conversely, upper water layers can cool when their clarity increases following liming; then deeper layers can warm with the greater penetration by solar energy.

In the ELS study, transparencies following liming markedly decreased only in Mountain Pond, and only during the first summer following liming (Schofield et al. 1986). Prior to liming and after reacidification this lake was essentially homothermal during the summer, with temperatures generally above 20°C (68°F). But during the first summer following liming, stratification caused cooler water temperatures at depths below 4 m (Figure 4). These lower temperatures provided improved habitat conditions for trout.

Lake liming also can often lead to reduced concentrations for both total and dissolved metals (e.g., Driscoll et al. 1989). These decreased concentrations can result from (1) the direct precipitation of the metals due to their reduced solubilities at more basic pH levels; (2) the formation and precipitation of relatively insoluble metal hydroxides in the more basic waters; or (3) settling of plankton that contain elevated metal concentrations (Driscoll et al. 1987, Fraser and Britt 1982, Dillon et al. 1979).

Specific for aluminum, field observations suggest that changes in solubilities following liming may temporarily increase its potential toxicity as aluminum hydroxide precipitates on fish gills (Muniz and Leivestad 1980). Laboratory studies have shown that lower pH levels in water solutions near the gill can cause aluminum binding to organic ligands and/or aluminum hydroxide precipitation on gill epithelia, which can lead to potential ionoregulatory and respiratory stress, and eventually to death (Mount and Marcus 1989). Caged and free swimming fish exposed to changing water quality conditions in the ELS study and a related study, however, showed no detectable adverse responses during liming due to changes in dissolved aluminum concentrations (Gloss et al. 1987, 1989).

Figures 5 through 7 depict responses for field pH, acid neutralizing capacity (ANC or alkalinity), calcium concentration, and total aluminum in Trout, Mountain, and Indigo ponds, respectively. These figures show the changes in these four chemical variables at monthly intervals, which include the month immediately before liming of each lake and extend for about three

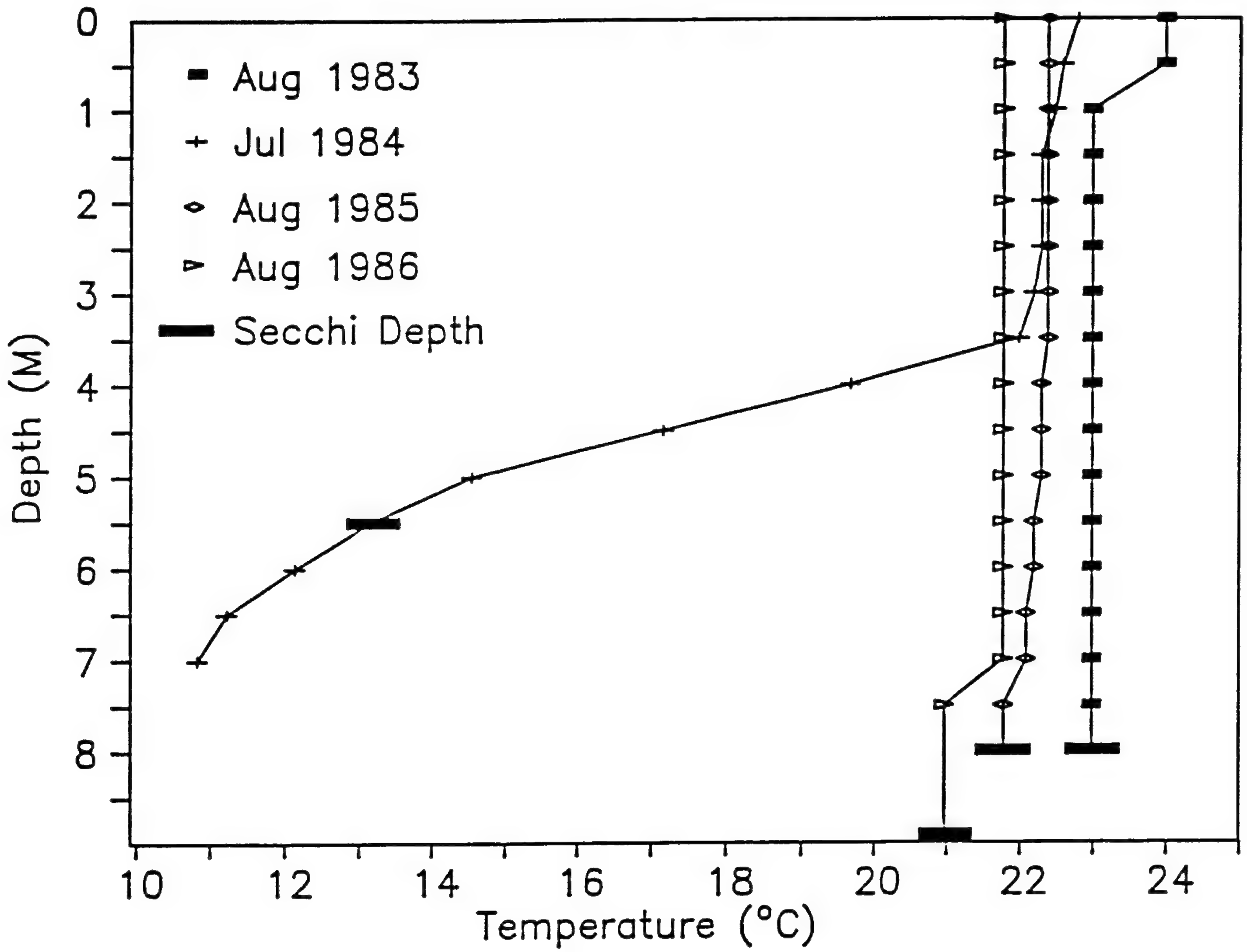

Figure 4. Temperature profiles in Mountain Pond during the summers of 1983 through 1986, shown with concurrent Secchi depth measurements (the depths where light intensities are 10-15% of those occurring at the surface).

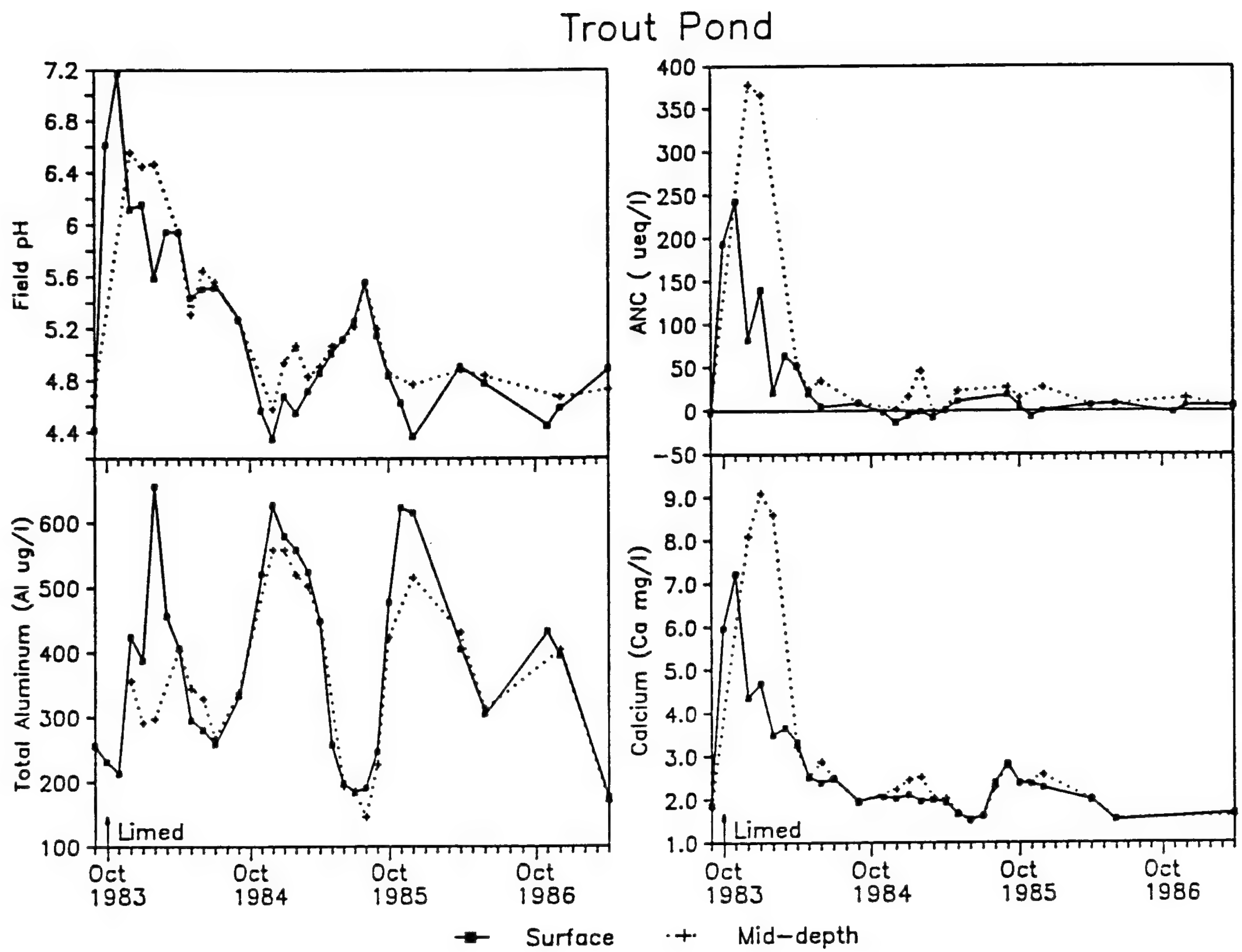

Figure 5. Sampling results for field pH measurements, acid neutralizing capacities, total aluminum, and calcium for Trout Pond.

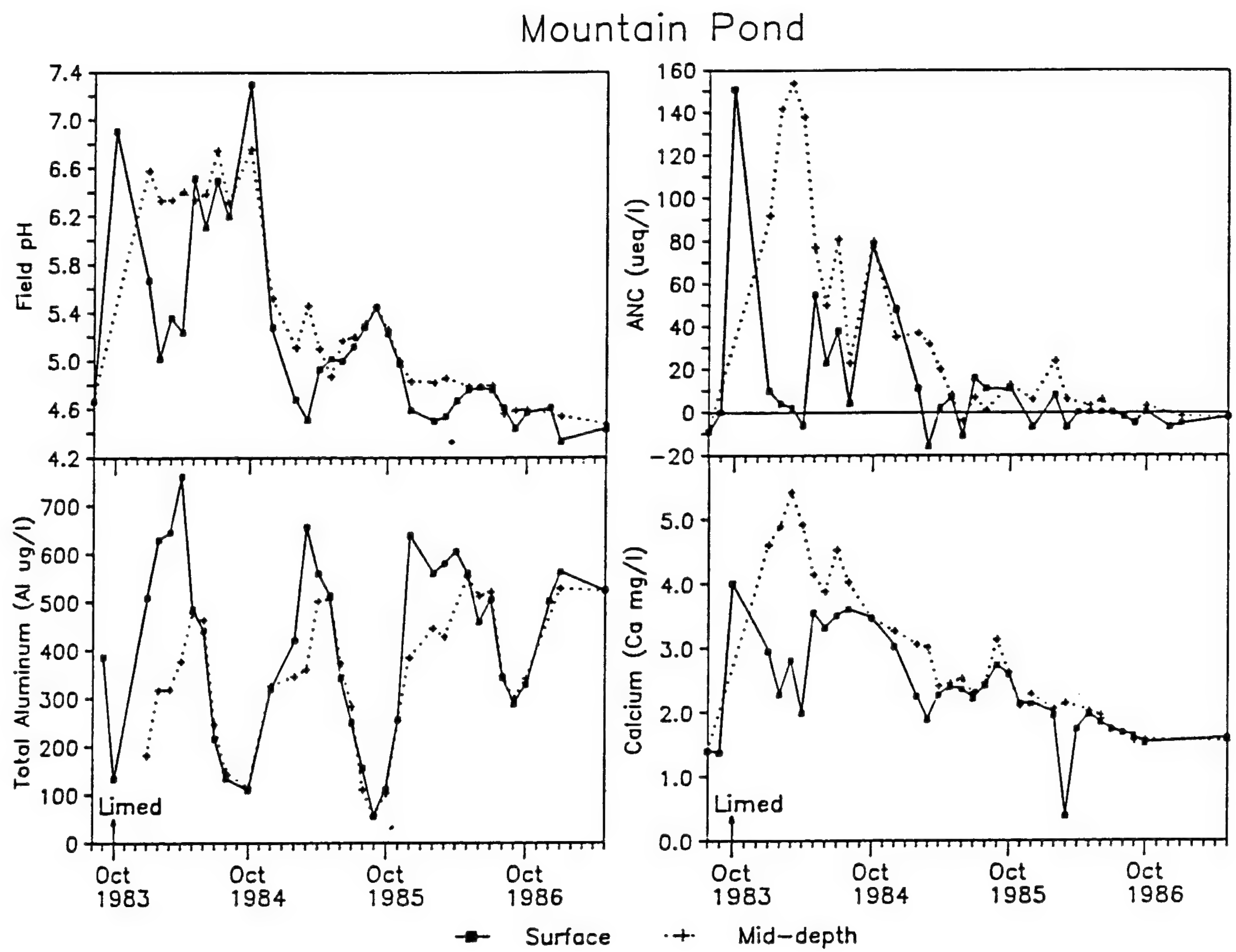

Figure 6. Sampling results for field pH measurements, acid neutralizing capacities, total aluminum, and calcium for Mountain Pond.

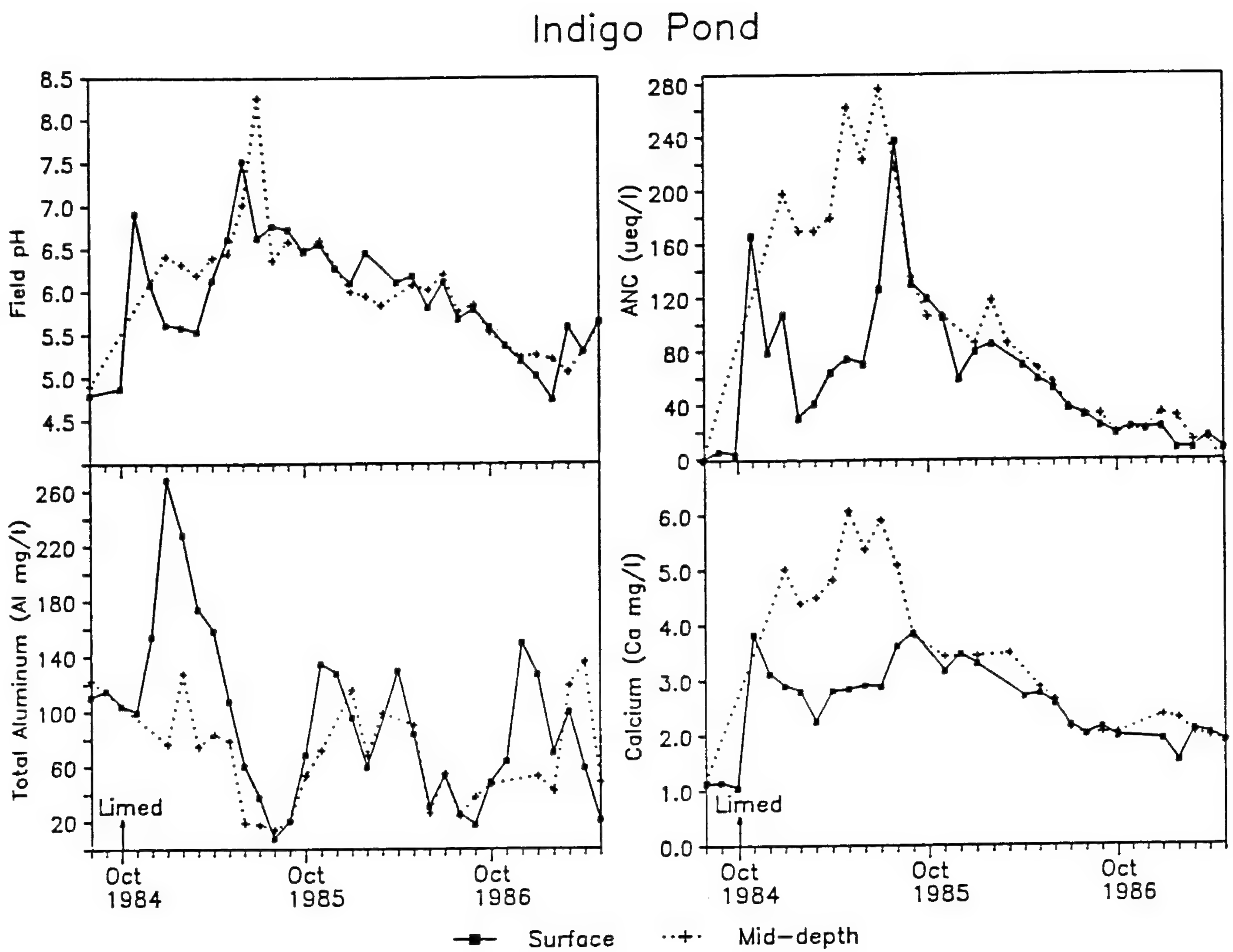

Figure 7. Sampling results for field pH measurements, acid neutralizing capacities, total aluminum, and calcium for Indigo Pond.

years after liming. The plots show data for samples collected from the upper 1 m (3.3 feet) and from near the mid-depth of the water column during each sampling date at each lake.

Increases in pH, ANC, and calcium were observed in all ELS lakes immediately after liming. However, total aluminum concentrations either decreased slowly (particularly in the deeper waters) or showed little immediate response to the treatments. In contrast, monomeric aluminum concentrations generally decreased rapidly as pH increased following treatment. For example, comparison of aluminum speciation in Mountain Pond before and after liming indicates a shift from predominantly labile monomeric aluminum to a predominance of acid soluble forms (colloidal and/or polymeric) following liming during periods of high pH (Figure 8).

In most ELS lakes, continued dissolution of settled limestone in the deeper waters resulted in trends of increasing hypolimnetic calcium concentrations and ANC generation during periods of stable stratification in winter and summer (Schofield et al. 1986). In those lakes exhibiting complete spring and fall overturn, pH, ANC, and calcium tended to increase in the upper water layers and decrease in the deeper layers following mixing and restratification (e.g., Highrock Pond). Lakes having incomplete overturn (e.g., Big Chief, Pocket and Silver Dollar ponds) maintained very high ANC and calcium concentrations. However, surface layers of these ponds reacidified more rapidly due to the isolation of the deep water alkalinity source.

Differences in the dynamic patterns for four chemical variables, as exemplified for the three lakes in Figures 5 to 7, appeared to be primarily due to differences in the hydrologic patterns among the ELS lakes. Recall from Table 1 that retention times (or water exchange rates) in these three ponds ranged from about 1.2 months for Trout Pond, to 9 months for Mountain Pond, to greater than 14 months for Indigo Pond. In general, the influence of liming on ANC lasted about 7 months in Trout Pond, about 15 months in Mountain Pond, and through 34 months in Indigo Pond.

These plots show intervals in all three ponds where abrupt episodic changes in the chemical variables occurred. This emphasizes the overall importance of meteorologic and hydrologic events in the watersheds in exerting important influences on the water qualities in these lakes. This is particularly evident in the plots for aluminum, which show that while liming apparently did cause a net short-term reduction in aluminum concentrations in the three ELS lakes, the long-term influence of liming was dampened by seasonal hydrologic events. In fact, episodic reintroduction of acidic, aluminum-rich run-off water to the upper layers of these lakes during the winter and spring months led to marked changes in aluminum speciation following spring overturn and mixing with deeper neutral waters (Schofield et al. 1986). Low water temperatures in the ELS lakes during and for the first six months after treatment also may have contributed to the persistence of high total aluminum levels as a result of slow hydrolysis and precipitation reactions (Schofield et al. 1986).

For these three ELS lakes in general, and for Trout and Mountain Ponds in particular, the mitigative influence of liming was compromised by periodic, seasonal flows of acid and aluminum bearing waters from the watersheds into

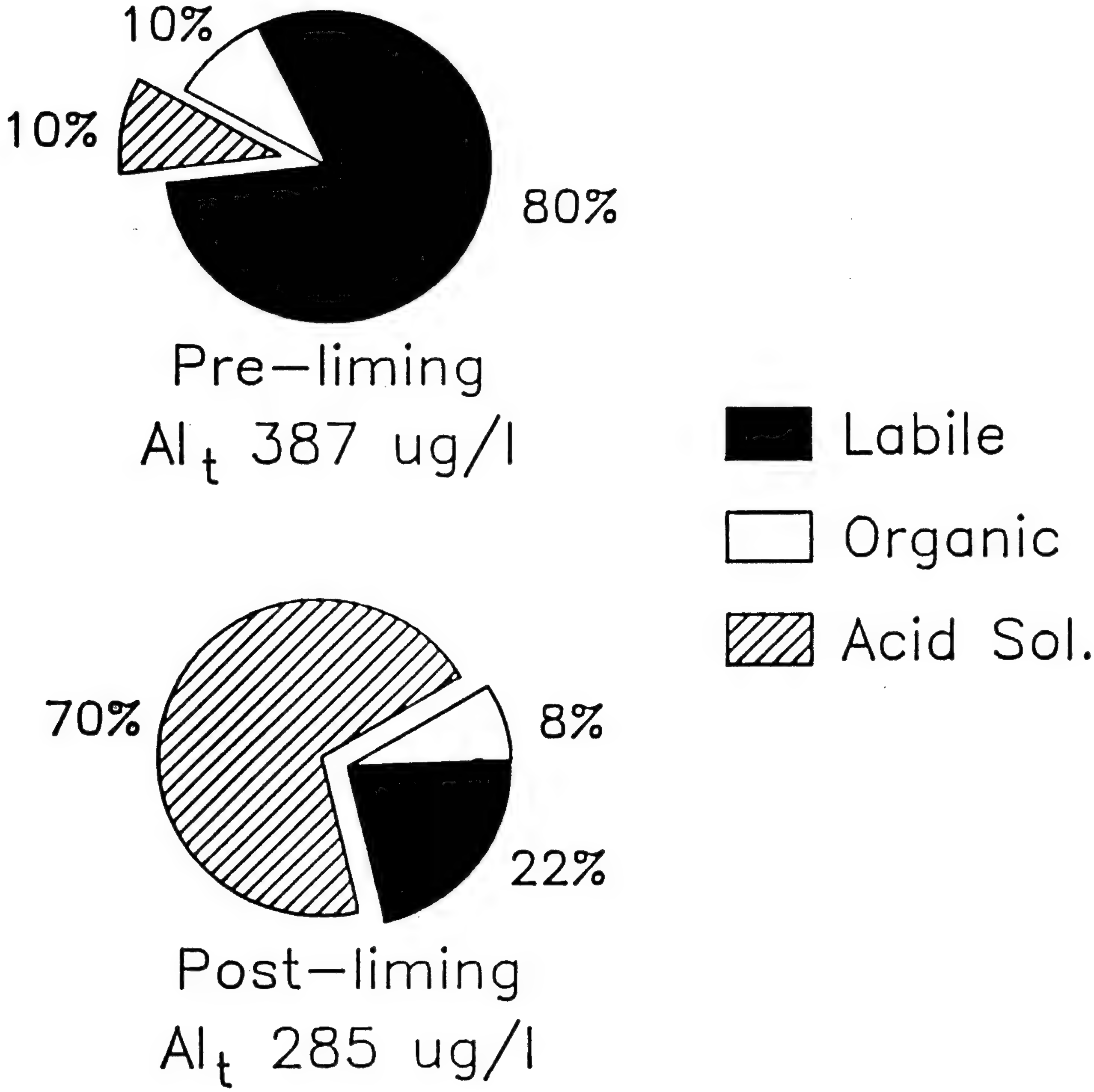

Figure 8. Aluminum speciation in Mountain Pond before (September 1983) and after (July 1984) liming (percentages are of total aluminum).

the lakes. This indicates that the success of liming in mitigating the effects of adverse water qualities on aquatic organisms can depend heavily on the seasonal flows of water through lakes. Thus, to best forecast the potential success of liming, it may be necessary to quantify as well as possible prior to liming the seasonal changes in the exchange of waters through lakes.

RESPONSES BY STOCKED BROOK TROUT INTRODUCED AFTER THE LIMING OF ELS LAKES

The ELS lakes were stocked using two groups of interstrain hybrid brook trout: Temiscamie x selected domestic, and Temiscamie x un-selected domestic brook trout. The selected hybrids were the first generation offspring from domestic females screened for presumed increased tolerance to acidity and Temiscamie males. The un-selected fish were offspring of Temiscamie males and un-screened domestic females. General characteristics of these fish were described by Flick and Webster (1964).

Following their one-time liming, the treated ELS lakes were stocked each Fall from 1983 through 1985 with equal numbers of both groups at a rate of approximately 50 fall fingerlings per group per surface hectare (20 per group per acre) of lake. Fish for each stocking were distinctively fin clipped for identification during future captures made from each lake. Numbers of fish captured during spring and fall trap nettings were used to calculate population and survival estimates for each group and each stock introduced into the lakes.

After liming and stocking, three of the ten ELS lakes (Little Rock Pond, Silver Dollar Pond, and Pocket Pond) developed severe oxygen depletion throughout much of the water column during extended periods of each year, most generally in the summer, but also occasionally in the winter. (Little Rock Pond, due to its high flushing rate, reacidified within less than six months after liming.) These concentrations were often below the tolerance limits for brook trout (Raleigh 1982). Therefore, in addition to high acidities, low oxygen concentrations probably were also a primary determinate of brook trout survival in these ponds during reacidification. Since our interest was to investigate the effects on survival by acidity and liming related variables, data from these three ELS lakes were not included in population or survival analyses.

Survival by "Acid Tolerant" and "Normal" Fish Stocks

When data on group survival from the ELS lakes were analyzed as a whole there was no significant relationship between group and survival ($P < 0.05$). Differences among group survivals for each year class in each lake is shown in Table 6. This table shows the proportional capture (K_2) of selected versus unselected stocks for each year class of brook trout from both the spring and fall trap nettings. The K_2 estimates were calculated assuming equal probabilities of capture (Skalski et al. 1983).

These results show no definitive differences between group survivals in the lakes. Fish from the selected group may have fared better in Big Chief

Table 6. Proportional abundance (K_2) of selected and un-selected brook trout in ELS lakes (K_2 = N selected / N unselected; Skalski et al. 1983).

Lake	Year Class	Census Period					
		5/84	10/84	5/85	10/85	5/86	10/86
Big Chief	1983[1]	1.02	0.95	nr[2]	1.57	ns[3]	5.00*
	1984			1.12	0.83	1.40	1.80*
	1985					nr	0.38*
Mountain	1983	1.14	0.95	ns	0.93	ns	ns
	1984			nr	0.59*	ns	ns
	1985					nr	ns
Highrock	1983	0.32*	0.38*	nr	0.27*	nr	nr
	1984			ns	0.90	nr	1.19
	1985					ns	ns
Trout	1983	1.24	0.97	ns	ns	ns	ns
	1984			ns	ns	ns	ns
	1985					ns	ns
Jones	1984			1.04	0.85*	0.92	0.90
	1985					ns	0.41*
Indigo	1984			nr	1.19*	nr	1.29
	1985					nr	1.39*
Barto	1984			0.98	1.14*	ns	ns
	1985					0.31*	nr

[1] Selected / unselected stocking ratio = 0.27 for 1983 year class in Big Chief Pond

[2] nr = no captures or recaptures for one group

[3] ns = no survivors captured in either group

* $K_2 \pm 95\%$ confidence interval did not include $K_2 = 1.00$

and Indigo ponds, while fish from the unselected group may have had some advantage in Highrock and Jones ponds. But, overall, there was a low capture of surviving fish from either group for most ELS lakes during the period beyond one to one-and-one-half years after liming.

As with survival, there were no consistent differences in growth rates between the two groups (Schofield et al. 1986). The lack of difference between the groups for either survival or growth may relate to the relatively rapid reacidification of the lakes. The pH levels in most of the limed ELS lakes rapidly decreased to levels intolerable to both groups. The bimodal distribution of the monthly pH measurements for the ELS samples, with fewer samples between pH 5.5 and 6.0 (Figure 9), indicate that the lakes passed rapidly through this poorly buffered region as they lost ANC and reacidified to pH levels below 5.0.

Because the selected and un-selected groups responded similarly during the ELS project, it may be interpreted that there is no particular advantage in stocking fish from the selected group as being tolerant to highly acidic conditions. However, this group may offer stocking options for waters that are marginally acidic, but that do not typically have pH levels as low as occurred in the ELS lakes following reacidification. Some previous studies have indicated that selected strains do perform better in acidic environments (cf., Flick et al. 1982). Thus, it is possible that stocks selected for acid tolerance would display better survival in those limed lakes having slower flushing rates (>1 per year), slower reacidification rates, and/or reliming applications. The ELS results, however, were not definitive in this regard.

Relationship of Water Chemistry and Fishery Changes to Survival and Growth

Fish populations may respond either to changes in environmental variables remaining by the population (density independent factors) or to changes in variables altered by activities of the population (density dependent factors) or to a combination of both. To evaluate whether these factors affected the brook trout stocked into the ELS lakes, we first used correlation and regression analyses to examine how water quality affected brook trout survival and growth. Then, multiple regression analyses were used to examine how changes in standing stocks and densities of brook trout, in addition to changes in water quality, related to differences observed in mean individual growth rates and in total population growth rates for the ELS brook trout.

Since the two groups of brook trout stocked into ELS lakes showed no consistent difference in survival after stocking, no distinction was made between the groups during the correlation and regression analyses. Each stocking was, however, treated as a separate population (cohort) in each lake and the survival and growth values from both groups were included in our analyses. Also, since several spring population estimates could not be calculated because low numbers of fish were captured, these estimates were excluded from analyses. Thus, while most results for brook trout survival and growth represent changes in a fish population over a six-month period, a few values represent changes over a one-year period. We combined the six- and twelve-month data to maximize the information available for analysis. (Results and interpretations obtained using the combined data were similar to

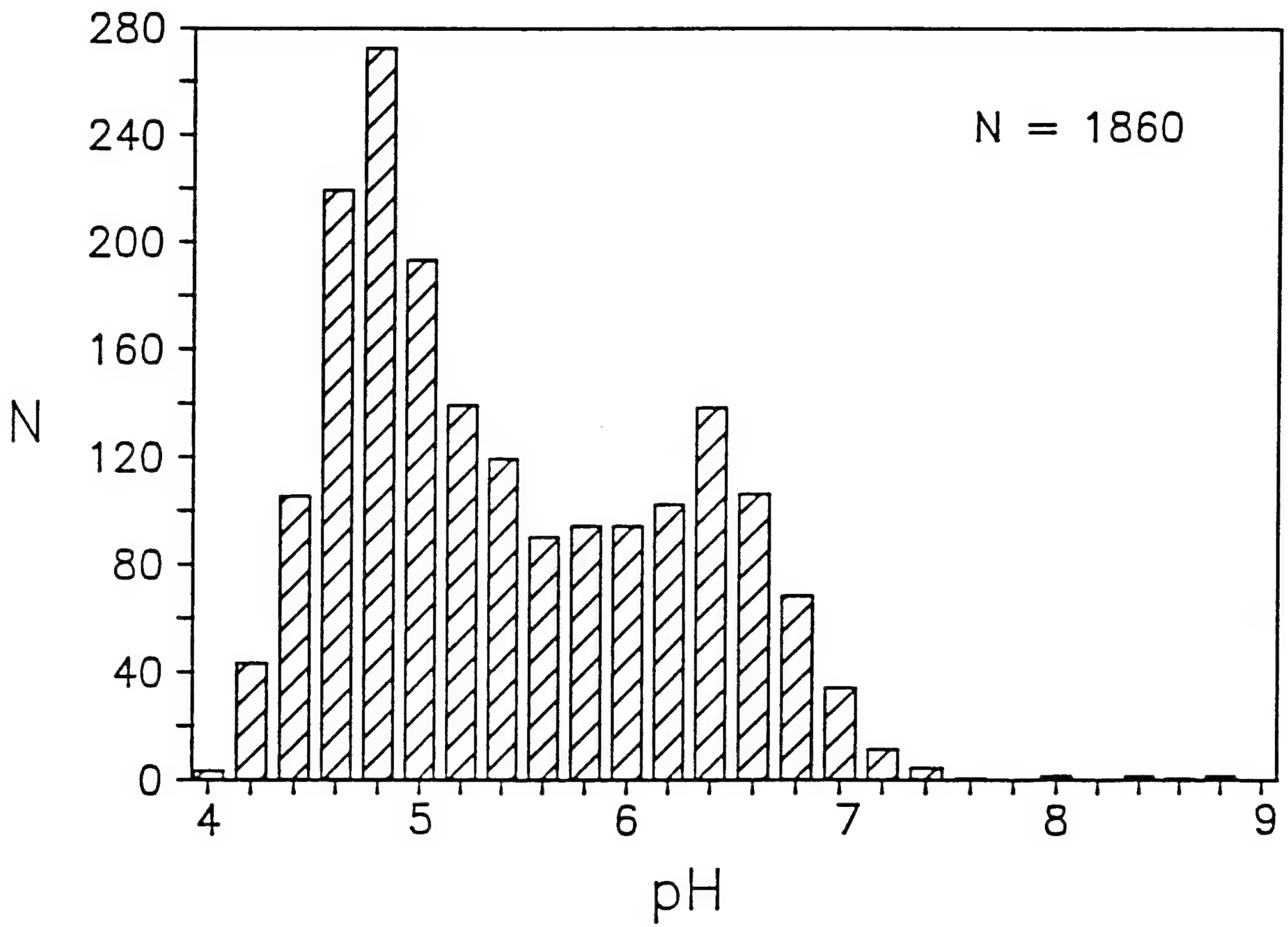

Figure 9. Frequency distribution of monthly field pH measurements for ELS lake samples, 1983-1986.

those obtained from separate analyses using either six- or the twelve-month based data individually.)

For each survival value computed, analytical results obtained for each water chemistry variable from a lake were averaged over the same 6 or 12 months. Since survival values are proportions, survival values were transformed using arcsin square root functions prior to analysis. Correlation analyses revealed that values for field pH, acid neutralizing capacity (ANC), and calcium (Ca) were all positively and significantly correlated to survival and to themselves (Table 7). Whereas, labile monomeric aluminum (Al) was negatively and significantly correlated to survival, pH, ANC, and Ca (Table 7).

All possible subsets regression was used to determine the combination of field pH, ANC, Ca, and labile monomeric Al that explained a maximum of the variation observed in survival. All subsets regression has an advantage over stepwise regression because it examines the significance of each equation derived using all possible combinations for the independent variables of interest. In stepwise regression, multiple correlations among independent variables can cause exclusion of significant variables from the final equation. In fact for these analyses, stepwise regression resulted in an equation that included only field pH as an independent variable. In contrast, all subsets regression included field pH, ANC, and Ca in the equation that best "explained" the arcsin, square-root-transformed survival (adjusted R^2 = 0.26):

$$\text{Survival} = -1.022 + 0.413\ \text{pH} + 0.007\ \text{ANC} - 0.276\ \text{Ca}$$

The values in Table 7 indicate that these four chemistry variables were highly multicollinear (significantly high correlation among multiple independent variables). This relationship can cause unstable and unreliable results during multiple regression analysis, an instability shown by the different results obtained using stepwise and all subset regressions. Because of this and because the correlation analyses in Table 7 indicates significant correlations to exist between all variables, simple regression analysis was used to examine the relation of these four water chemistry variables to brook trout survival. Four regression models resulted, which are plotted in Figure 10 with the actual data from the lakes:

$$\text{Survival (arcsin, square root transformed)} = 0.42\ \text{pH} - 1.55$$

$$\text{Survival (arcsin, square root transformed)} = 0.16\ \text{Ca} - 0.29$$

$$\text{Survival (arcsin, square root transformed)} = 0.005\ \text{ANC} - 0.51$$

$$\text{Survival (arcsin, square root transformed)} = -0.001\ \text{Al} - 1.02$$

Of the four chemical variables, the model for field pH best predicted brook trout population survival, as indicated by a correlation (R^2 = 0.23, Table 7) only slightly less than that obtained for the best equation from the all subsets regression (R^2 = 0.26). However, the correlations for all four regressions were fairly close (R^2 = 0.12 to 0.23, Table 7). These results indicate that any one of the five regression equations could be used to predict survival with about equal reliability.

Table 7. Matrix of correlation coefficients between water chemistry and survival variables.

	pH	ANC	Ca	Al[1]	Survival
pH	1.00				
ANC	0.80*	1.00			
Ca	0.80*	0.91*	1.00		
Al	-0.78*	-0.48*	-0.42*	1.00	
Survival	0.48*	0.44*	0.34*	-0.36*	1.00

[1] Labile monomeric aluminum
* P < .01

Although survival regressions computed using each of the four chemical variables were highly significant, the data show a wide scatter about the regression lines (Figure 10). These results and that from the all subset regression indicate that 77 to 88% variance of the brook trout survival in ELS lakes was unexplained by the chemical variables alone included in these regressions. The poor overall fits of these models may be a consequence of averaging water chemistry values over the 6- to 12-months periods to match each 6- to 12-month period included in estimates of brook trout population survival.

Averaging water chemistry values may mask the most important water chemistry values, such as may occur during episodic runoff events. However, when we explored this possibility using minimum pH, Ca, ANC, and maximum Al values measured during each 6- to 12-month period, we found that these regressions yielded results that were little better than results obtained using mean chemical conditions. It is possible, however, that the measured chemistry data did not include the worst conditions encountered by the fish in these lakes.

Growth patterns for the brook trout stocked into the ELS lakes were similar to those found for survival, with the slowest growths occurring in lakes with the greatest hydrogen ion concentrations (Schofield et al. 1986).

We then examined the possible interaction of brook trout standing crops and densities with adverse water quality conditions in possibly influencing

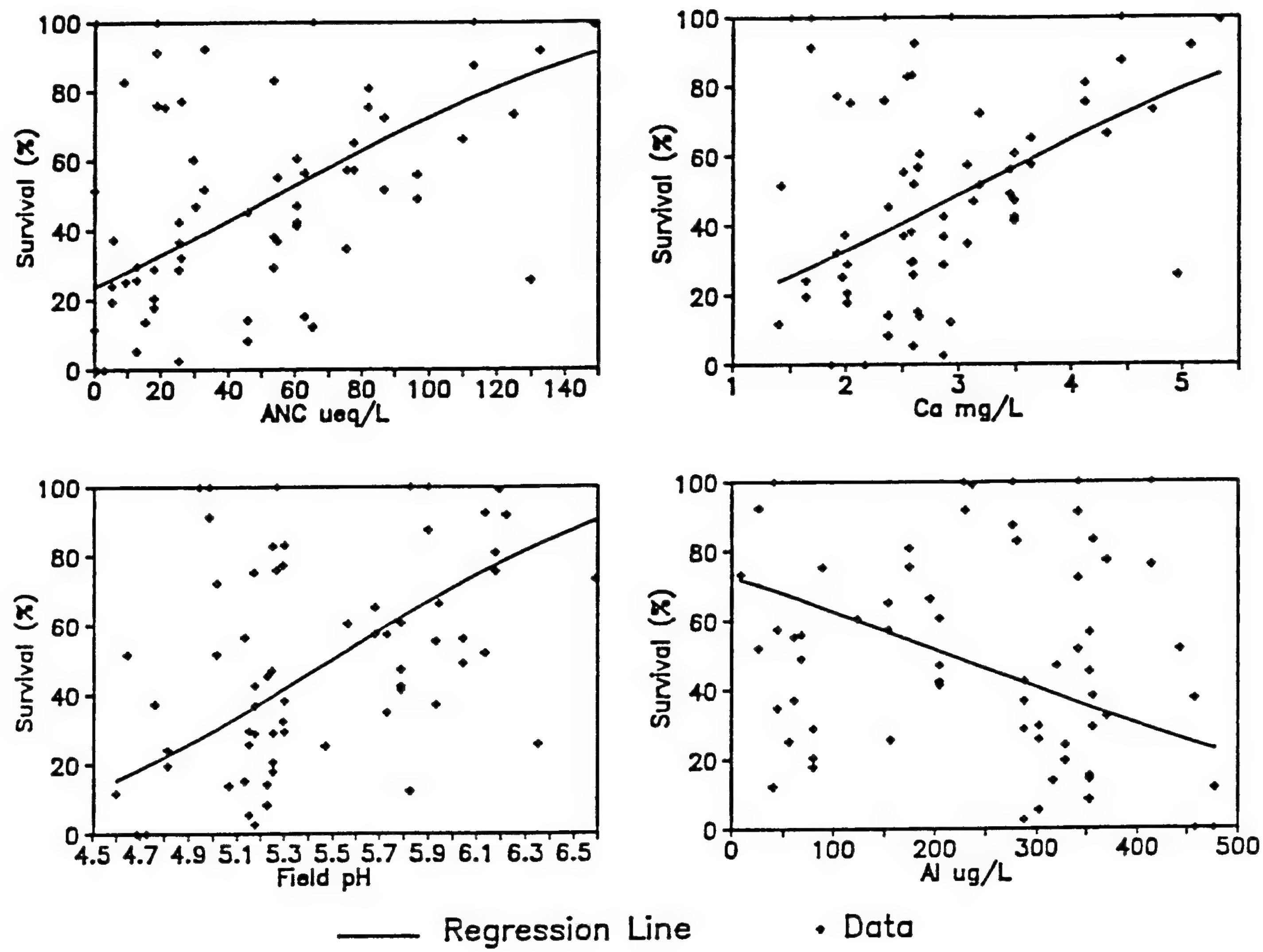

Figure 10. Plots of data and regression results showing brook trout survival in ELS lakes as functions of field measured pH, acid neutralizing capacities (ANC), labile monomeric aluminum (Al), and calcium (Ca).

growth by the ELS brook trout. Hydrogen ion concentration, the chemical variable most related to brook trout effects in the ELS lakes, was used as the indicator of water quality conditions. As shown in Figure 11, mean change in weight for individual brook trout was significantly related ($R^2 = 0.871$, $P < 0.05$) to both standing crop and stressful water quality conditions in these lakes, as indicated by hydrogen ion concentration.

These effects on growth are consistent with laboratory findings of slower growth rates in brook trout as a consequence of physiological stress induced by exposure to elevated acid and aluminum concentrations in low calcium waters (Baker 1984, Mount et al. 1988). Acid induced stress reduced metabolic efficiencies and/or reduced feeding activities in these laboratory studies.

Perhaps a more important relationship shown in Figure 11 is that weight loss in individual trout would occur for about half of the combinations of brook trout standing stocks and lake pH levels included on the plot. Similarly, Figure 12 shows that mean growth by individual ELS brook trout decreased substantially with both increased hydrogen ion concentrations and increased brook trout densities; negative growth would also occur for about one half of the displayed combinations. These relationships strongly indicate that food limitations or impaired feeding activities may be limiting growth rates in ELS lakes, particularly as water quality changes back to more acidic conditions following liming.

While laboratory studies have shown that feeding behavior can be depressed in brook trout due to acid stress (e.g., Mount et al. 1988), the ELS data suggest a response due more to food limitations. Figures 11 indicates that as brook trout standing crops increased, mean individual growth rates decreased at approximately equal rates throughout the range of hydrogen ion concentrations shown. Figure 12 similarly shows that increases in densities of ELS brook trout were accompanied by about equal decreases in mean growth rates across the range of hydrogen concentrations. These results, therefore, are important indications that high competition for food among the higher standing crops and densities of brook trout may be depleting food stocks and restricting growth in the ELS lakes.

Other studies in Adirondack lakes as well as in Swedish lakes indicate that trout populations stocked into recently limed lakes can rapidly decimate populations of large invertebrates, a primary food resource for trout (Evans 1989, Gloss et al. 1985, Nyberg 1984, Schofield et al. 1989). Experimental lake studies in Canada also have found reduced fish growth occurring as a consequence of limited food availability in response to lake acidification (e.g., Mills et al. 1987).

Figure 13 further shows that total production by fish populations in the ELS was not increased by the presence of larger standing crops of fish. While total population production did strongly decrease with increasing hydrogen ion concentration, it had only a slight negative relationship to standing crop. Thus, larger standing stocks and larger densities of ELS brook trout did not lead to larger population productivities. It, instead, led to reduced growth by individual brook trout and smaller fish, as shown in Figures 11 and 12.

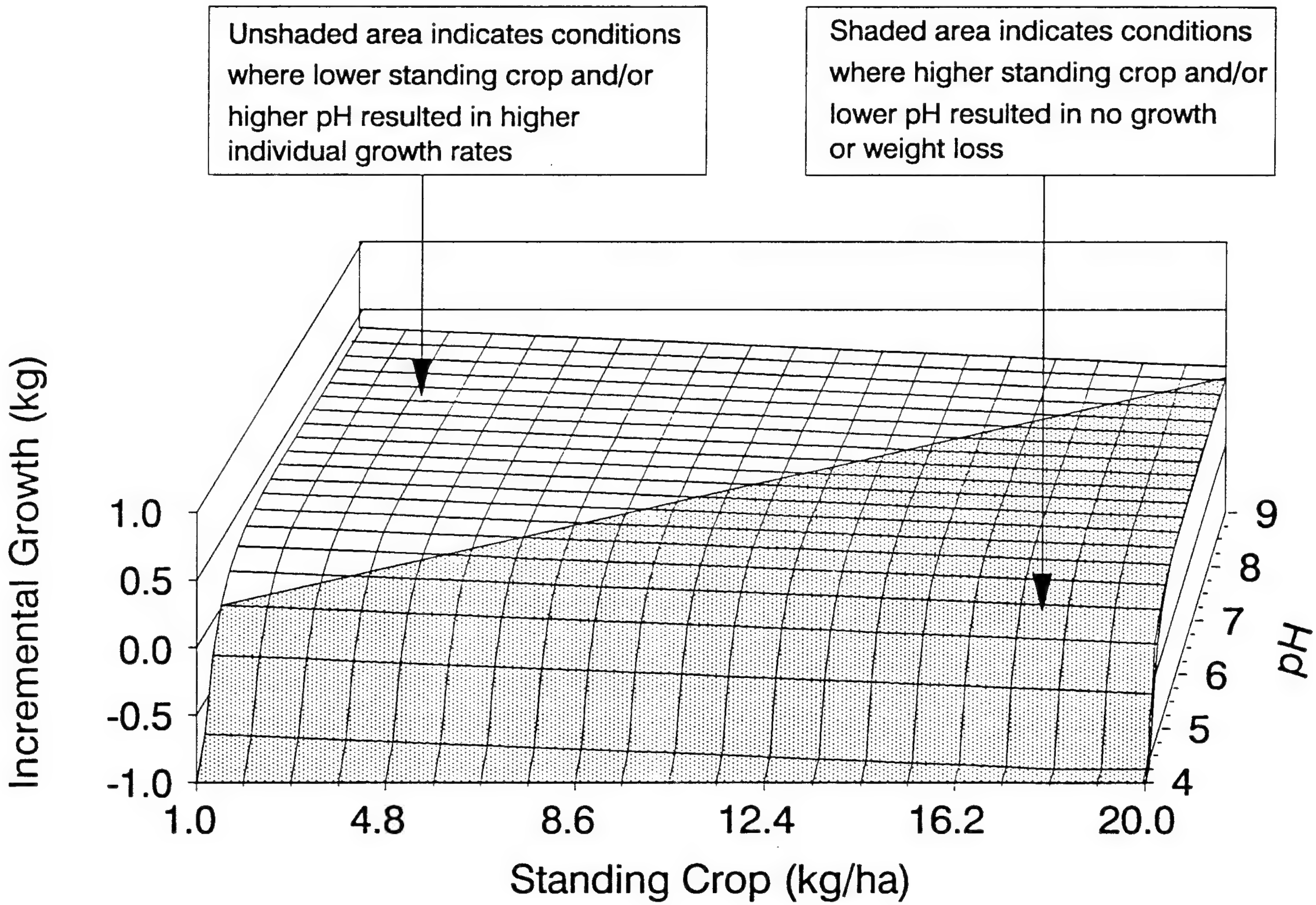

Figure 11. Incremental growth (G; kg) in weight for individual brook trout as a function of field pH (calculated as hydrogen ion concentration, H; μeq/l) and estimated standing crop (SC; kg/ha) of brook trout in ELS lakes [$G = 0.378 - 0.0149\ SC - 0.0196\ H$; $R = 0.93$; $N = 19$].

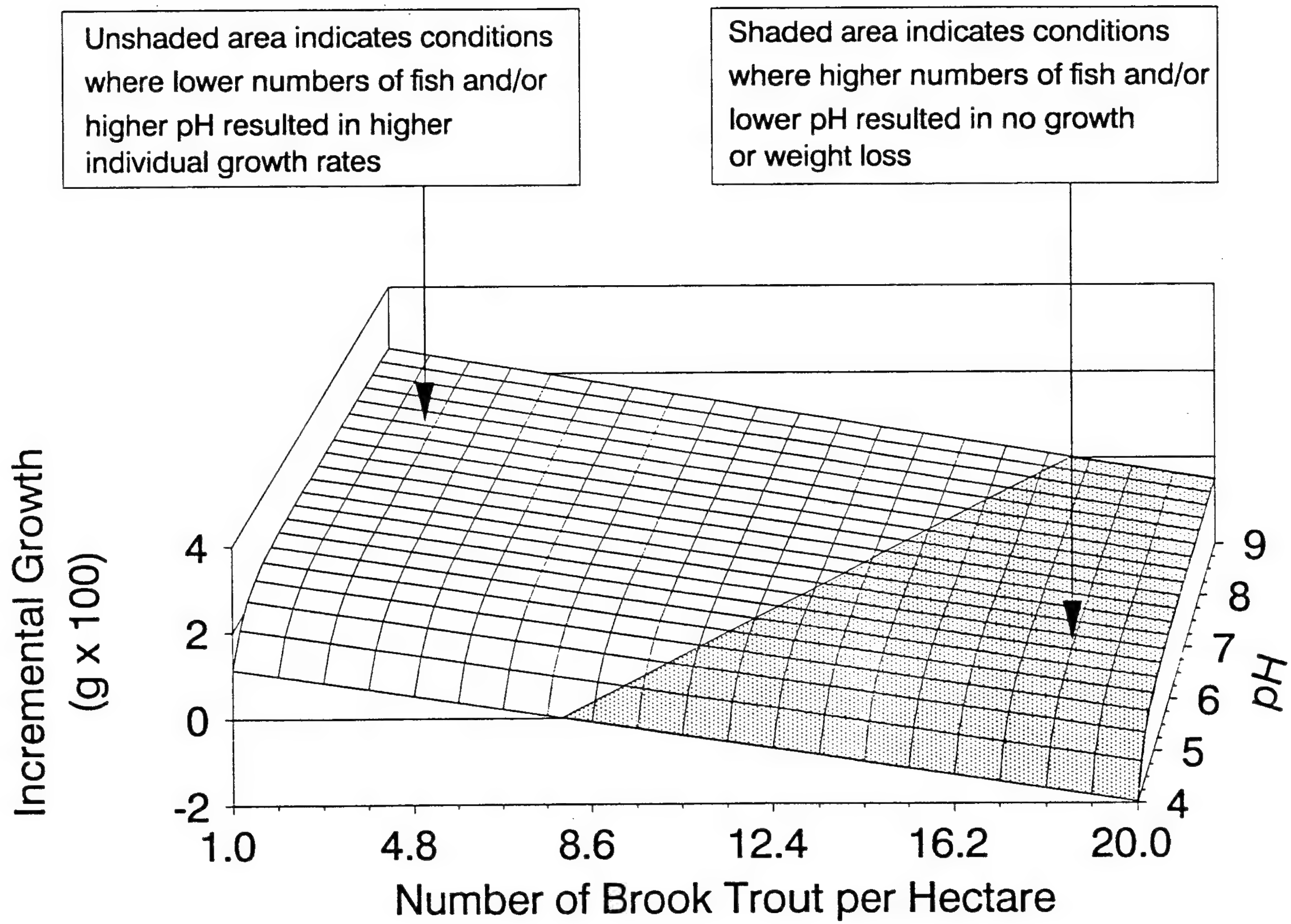

Figure 12. Incremental growth (G; g x 100) in weight for individual brook trout as a function of field pH (calculated as hydrogen ion concentration, H; μeq/l) and estimated number of brook trout per hectare in ELS lakes [G = 275.6 - 16.32 D - 1.45 H; R = 0.79; N = 19].

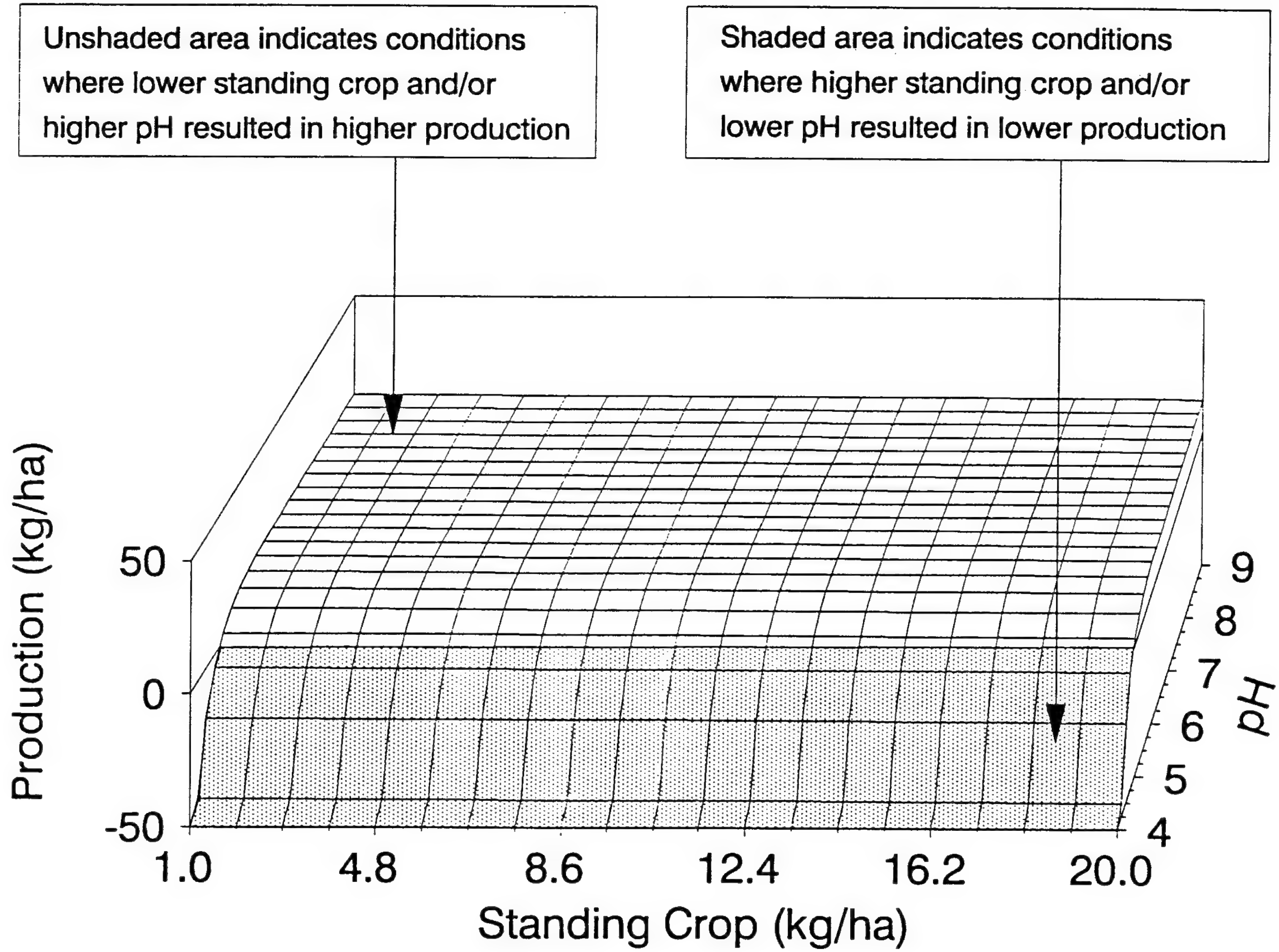

Figure 13. Population production (P; kg/ha) for stocked brook trout as a function of field pH (calculated as hydrogen ion concentration, H; μeq/l) and estimated standing crops (SC; kg/ha) of brook trout in ELS lakes [P = 13.21 - 0.0434 SC - 1.02 H; R = 0.70; N = 18].

These results suggests that the food resources in ELS lakes were capable of supporting only a limited production of fish, which varied across the range of water quality conditions investigated. When greater densities and standing crops of stocked fish were present, mean growth per fish was very limited or even negative. But when fewer fish and smaller standing crops were present, larger individual growth rates and larger fish resulted.

Either density dependent or behavior dependent effects on growth or survival in stocked fish can confound the interpretation of chemical effects in limed lakes. Such effects, in fact, may account for much of the unexplained variability found in the survival of ELS populations. That is, much of the variance remaining unexplained in the regression analyses for survival using chemical variables discussed above may be attributable to food limitations or feeding reductions. The low and negative grow rates found in the ELS brook trout caused by limited food availability may also have depressed survival of the stocked fish. This conclusion is supported by the fact that the equation for the plot shown in Figure 11 accounts for over 87% of the variation in weight change in the stocked brook trout. The implications of these findings are presented in the next section, which discusses stocking and managing strategies for limed Adirondack lakes.

While most lakes used in the ELS project had high flushing rates, which led to fairly rapid re-acidification rates, their flushing rates were much less on average than small acidified Adirondack lakes (cf., Figure 3). The regressions in Figure 10 show that fish population declines during re-acidification were associated with decreasing pH, ANC and Ca, and with increasing aluminum. The single applications of limestone appeared inadequate to maintain suitable water quality for trout survival in most of the ELS lakes over a prolonged period. Protection of fish populations inhabiting a lake with a relatively small size and high flushing rate, such as characterize most of the ELS lakes and many more of the acidified Adirondack lakes, probably requires at least annual applications of limestone or, perhaps, limestone treatments of their watersheds.

DEVELOPING BROOK TROUT STOCKING AND MANAGEMENT STRATEGIES FOR LIMED ADIRONDACK LAKES

Often, the ultimate desire for a managed fishery is that the population will naturally maintain adequate reproduction rates yielding enough fish to sustain satisfactory harvest success for the realized fishing pressure. Unfortunately, many lakes lack appropriate spawning or rearing habitats for brook trout. Therefore, it often is necessary to augment, or even totally maintain a brook trout fishery by stocking. Stocking also is at least initially necessary where mitigative liming is conducted to restore fisheries in lakes where historical fish populations were depleted or eliminated due to acidification.

Given the need to stock brook trout into a lake following liming, appropriate stocking procedures should be followed: necessary permits to stock fish need to be obtained for private lakes, appropriate stocking times and rates for the lake established, and sources for appropriate fish stocks must be identified.

LEGAL CONSIDERATIONS

Before private stocking of fish into any private or public lake in New York, a permit to do so must be obtained from the State Department of Environmental Conservation. Appropriate application information is available through the NYSDEC's regional fisheries biologists. There is no cost for completing this simple procedure. Similar permits are also required for other states, and necessary application information can be obtained from each state's fishery management agency.

Under the State Land Master Plan for the Adirondack Park, the most restrictive guidelines apply to "wilderness areas." These lands are to be "managed to preserve, enhance and restore, where necessary, its natural conditions" (NYSDEC 1988). This has been interpreted to permit various fishery management activities, including liming, fish stocking, pond reclamation, barrier dam construction and maintenance, resource surveys and inventories, implementation of fishing regulations, and program planning; use of motor vehicles are not permitted, but use of aircraft and motorized equipment is permitted when such use is required to preserve wilderness values and resources (NYSDEC 1988). In "wild forest areas" of the Adirondacks, motor vehicles are permitted, in addition to the above cited uses, when necessary for fish and wildlife resource preservation and enhancement (NYSDEC 1988).

STOCKING TIMES AND RATES

Fall stockings of brook trout fingerlings were used in the ELS lakes. Either spring brook trout fingerlings (2 to 3 inches long, 2 to 3 months old) or fall fingerling (5 to 6 inches long, 7 to 8 months old) can be stocked into limed lakes. While both groups tend to reach catchable sizes at about the same time, survival of fall plants tend to be greater in most lakes. Since costs of brook trout from commercial hatcheries now range from about $25 to $60 per hundred for spring fingerlings and $50 to $95 per hundred for fall fingerlings, fall plants also tend to be most cost effective, since fewer are generally used. State fishery management agencies will supply current information about locations where stocking fish are available. State operated hatcheries in New York and most other states do not supply fish for stocking privately owned lakes.

In most Adirondack lakes impacted by acidic conditions and treated by liming, maximum stocking rates and growth rates are limited because of their generally lower natural nutrient levels and shorter growing seasons. Results from ELS lakes suggest that no more than 100 fall fingerling brook-trout per hectare (40 per acre) should be planted in limed Adirondack lakes.

Most brook trout live only three to four years in Northeastern U.S. waters. Without natural recruitment of brook trout to limed lakes, restocking generally will be required at two year intervals. Again, stocking of larger fall fingerlings is recommended for the same reasons presented above <u>plus</u> to possibly lessen the loss of the newly stocked trout through predation by those larger fish remaining from the previous stockings. Maximum restocking rates for most limed Adirondack lakes should again be at 100 fall fingerlings per hectare every two years or 50 fall fingerlings per hectare every year. The latter approach maintains a more "natural" mixture of fish in the lake as well as maintaining a more uniform year-to-year fishery available for angling.

Based on results from ELS lakes and from other studies, the oligotrophic lakes in the Adirondacks appear to support maximum brook trout standing crops of 10-20 kg/ha (9-18 lbs/acre) at production levels of 7-16 kg/ha/yr (6-14 lbs/acre/yr; Schofield et al. 1989). Additionally, results from ELS and from Hatch and Webster (1961) suggest that brook trout populations in these lakes should be managed to maintain maximum standing crops in the spring of 11-14 kg/ha (10-12 lbs/acre; Schofield et al. 1989).

When excessive numbers of fish are stocked into lakes, high competition among the stocked individuals for the available food organisms can result in reduced growth ("stunting") and reduced survival. As indicated above, trout populations stocked in limed lakes can rapidly decimate populations of prey organisms that constitute a significant fraction of the total initial food resource. Food limitations apparently had important affects on survival and growth in the ELS lakes.

Results from the ELS lakes clearly show that mean individual growth rates for stocked brook trout were substantially depressed at the higher standing crops and densities of brook trout. At the higher densities, the limited food resource was distributed among greater numbers of fish, limiting individual growth rates. At the highest densities of fish, the food resource was

apparently depleted and the resident fish lost weight. This relationship highlights the significance of limiting stocking rates in Adirondacks lakes that are comparable to the ELS lakes. Lower stocking rates reduce pressure on the food resource, leading to significantly better growth in stocked fish. Growth rates that could be sustained after five or more years of continued maintenance liming and stocking in these low productivity lakes remain unknown. It is likely, however, that under some lower stocking regimes, sufficient growth rates can be maintained to establish trophy class brook trout fisheries in some limed Adirondack lakes.

SELECTION OF THE BROOK TROUT STOCK

Fish strains that have different evolutionary histories often have different survival and growth rates after stocking. One study, for example, showed that a hatchery strain had poorer over-summer survival and growth rates in ponds, while having generally faster growth rates in hatcheries, relative to "wild" brook trout strains originating from New York Mountain lakes (Flick and Webster 1964). Also, hatchery strains of brook trout and reproductive crosses of hatchery and wild strains can be much more susceptible to fishing harvest than are wild strains (e.g., Flick and Webster 1964, Mason et al. 1967).

Different trout strains also appear to have different sensitivities to stress from elevated concentrations of acid and aluminum (see review by Flick et al. 1982). But other results from both laboratory and field studies reviewed by Flick et al. (1982) and from the ELS lakes were generally less conclusive about survival or growth advantages in brook trout selected for acid tolerance when stocked in acidic or limed waters. Lack of significant differences in these studies may be because the waters into which the fish were introduced were either too stressful or not sufficiently stressful to produce differences among the responses observed (Flick et al. 1982, Schofield et al. 1986).

Despite the general lack of definitive results among comparative studies, there is little doubt that differences in sensitivities of brook trout stocks to acidic water do exist (Flick et al. 1982; Wood et al. 1988a, b). Therefore, for surface-waters susceptible to acidification, it can be advantageous (1) to plant brook trout stocks thought to be less sensitive to potential impacts from acidity, and (2) to avoid those stocks thought to be more sensitive to such impacts (see also NYSDEC 1988). The lesser the stock's sensitivity to potential acidification impacts, the longer its population will likely survive as the limed water begins to re-acidify, and/or as the population encounters episodic events of acidic runoff waters. The Temiscamie strain and crosses of this strain with domestic hatchery stocks are both generally thought to be less impacted by acidic conditions (Flick et al. 1982).

ADDITIONAL CONSIDERATIONS FOR STOCKING LIMED LAKES

Survival by brook trout stocked into acidic waters may be increased by pre-stocking acclimation to elevated acid and aluminum concentrations. For the purposes of this discussion, "acclimation" in brook trout develops through the pre-stocking exposure over several days of these fish to sublethal concentrations

of acid and/or aluminum. This exposure can cause brook trout to become less sensitive to stress effects when exposed to these chemicals following stocking.

Laboratory studies show that acclimation of brook trout can significantly elevate concentrations of acidity and aluminum necessary to cause the same physiological stresses found in unacclimated brook trout inhabiting acid and aluminum contaminated waters (Wood et al. 1988b, c). The actual importance of brook trout acclimation in reducing possible impacts to field stocked trout remains less certain (Flick et al. 1982; Gloss et al. 1987, 1989). In most instances, however, since liming reduces both acidity and aluminum to below potentially toxic concentrations, pre-stocking acclimation would be unnecessary for fish stocked into most limed lakes.

Additional work is needed to (1) better identify brook trout strains best suited for use in acidic and limed waters, and (2) assess the overall importance of acclimation in stocked lakes. However, available information from the ELS study and from other studies indicates that populations of most brook trout strains are unaffected in waters above pH 6.0, and, either with or without acclimation, most are significantly affected in waters below pH 5.0 (Baker 1984, Haines and Baker 1986, Marcus et al. 1986). Thus, to protect brook trout fisheries in limed surface waters, one of the most important goals is to maintain acidities above at least pH 6.0.

SUMMARY AND CONCLUSIONS

SUMMARY OF THE EXTENSIVE LIMING STUDY

Liming the ELS lakes decreased lake acidities by consuming H^+ during various neutralizing reactions, increased lake acid neutralizing capacities (ANC), and increased lake calcium concentrations. Water transparency markedly decreased following liming only in Mountain Pond, and then only during the first summer following liming. This decrease led to lower water temperatures and a temporarily improved habitat for trout in the deeper waters of this pond. Aluminum concentrations in these lakes first had short-term reductions following liming, but long-term effects by liming on aluminum concentrations were compromised by seasonal hydrologic events. No adverse effects were observed to result from liming the ELS lakes.

Reacidification occurred fairly rapidly in most of the ELS lakes as meteorologic and hydrologic events in the watersheds exerted dominating influences on the water qualities. ELS results indicate that the success of liming in mitigating the impacts by acidic waters on fish will depend on the ability to select appropriate lakes for treatment and on implementing liming strategies that effectively neutralize seasonal flows of acidic waters through lakes.

Brook trout stocks that were selected for presumed acid tolerance had no consistent survival or growth advantages over unselected stocks in the ELS lakes. The general lack of consistent differences may have resulted from the relatively rapid reacidification of most ELS lakes. Assuming rapid reacidification was the cause, these selected stocks of brook trout may have advantages in lakes where the reacidification is slower than occurred in the ELS lakes, and/or where the lakes are relimed before low pH levels are reached.

Four chemical variables (pH, ANC, Ca, and Al) were significantly correlated with brook trout survival in the ELS lakes. Of these, pH marginally had the greatest relationship. Regression analysis of brook trout growth in these lakes, however, indicated that indirect density dependent or behavior related effects, in addition to direct effects by chemical variables, significantly affected brook trout survival and growth in the ELS lakes. Slow or negative growth rates may have been caused by reduced food intake in many of the stocked populations. Previous studies in the Adirondacks and in Sweden indicated that stocked populations in limed lakes can rapidly decimate food resources. Therefore, ELS results indicate that no more than 100 fall fingerling brook trout per hectare (40 per acre) every two years, or 50 per hectare annually, should be stocked into limed Adirondack lakes. Furthermore, lower stocking rates may provide opportunities to manage for trophy class fisheries.

POTENTIAL ROLES FOR LIMING IN THE MANAGEMENT OF ADIRONDACK REGION LAKES

Results from the ELS project and various other liming projects indicate that lake liming is a useful approach for mitigating current and continuing impacts due to surface water acidification. Results from the ALSC found that 3 lakes in the Adirondacks have pH levels below 4.0, while another 619 lakes have pH levels below 6.0. Even though these acidic lakes comprise 46% of the lakes in the Adirondacks, a relatively low percentage of these lakes meet the combined depth, area, flushing, and other habitat criteria that indicate their suitability for liming (Kretser et al. 1989). While the available results show that liming can improve the water quality for fish and other aquatic biota without adversely impacting natural resources in non-natural acidic lakes and streams, there is a somewhat limited potential that operational liming can substantially contribute to enhancing viable habitat for fisheries in the Adirondack region.

The potential negative impacts and positive benefits of liming, particularly as related to the Adirondacks, were recently reviewed by the NYSDEC (1988). Among the concerns listed for potential adverse impacts were

- Liming will cause reductions in populations of *Sphagnum* (a moss species requiring acidic habitats), which will result in wetlands comprised of species better adapted to less acidic habitat conditions.
- Use of hydrated lime, soda ash, or other highly basic materials in liming could produce rapid decreases in acidity that could cause the death of fish and other aquatic species not able to adapt to rapidly changing pH conditions.
- In the period of several days to several weeks following liming acidic lakes and streams, transitional changes in metal solubilities and speciation can create temporary conditions that are toxic to resident fish and amphibians.
- Although not necessarily considered a potential problem in the Adirondacks, liming could produce a competitive advantage in a less desirable fish species over a more desirable species.
- Liming will likely increase the biota diversity relative to that existing in an acidic lake prior to liming, but the resulting species composition may differ from that existing prior to any man-caused acidification.
- Committing to a liming program requires the allocation of funds to maintain the necessary liming, reliming, and monitoring activities.
- Liming creates various societal concerns, including (1) it may draw attention away from the resolve to reduce the primary causes of the acid deposition problem; (2) it may decrease the "wilderness nature" of designated wilderness areas; (3) it may increase human use of delicate natural resources, thereby speeding destruction of wider areas in the wilderness (e.g., increased human litter); and (4) it may result in the establishment of new water quality problems for aquatic species.

In evaluating these concerns, the NYSDEC (1988) concluded that the overall severity of the potential negative impacts on ecosystems related to liming were minimal, relative to the potential overall positive benefits from liming in improving water quality and associated habitat conditions for fish, other aquatic biota, and terrestrial wildlife. Additionally, they concluded that operational liming results in recreational and economic benefits that exceed societal concerns and economic costs for the small number of lakes they intend to treat in their operational liming program.

LIMITATIONS AND UNCERTAINTIES REMAINING ABOUT OPERATIONAL LIMING

Liming is only a temporary solution for the problem of surface-water acidification. A principal concern about liming, as was highlighted by the NYSDEC (1988: 76), is that it "draws attention away from resolution of [the] primary causes of the acid deposition problem." Large-scale liming is not an alternative to pollution control. But, as emphasized by Bergman (1988), lake liming is an approach through which the effects of acidification in surface waters can now be mitigated until the causes of acidification can be corrected. Additionally, following any significant reduction in acidic emissions and discharges, surface water resources can continue to be acidic over some yet undefined recovery time (perhaps a decade or more). Liming is a feasible approach to mitigate and speed resource recovery in certain lakes during this period.

Despite the potential benefits of operational liming, resource reacidification will likely continue; most lakes that are limed will need to be relimed in the future. Fish populations living in limed lakes also face uncertain potential threats due to short-term, episodic or pulse acidification during times of runoff accompanying major snowmelt or storm events. Snowpacks can accumulate considerable acidity. The rapid release of this acid during spring melts can produce flushes of acutely toxic waters through lakes and streams. Similarly, major rain storms can also produce rapid flushes of acidic waters, which can be toxic to resident biota. While recent research suggests that instream liming, watershed liming, and lake shore liming can reduce or eliminate episodic impacts to aquatic biota (e.g., Brown 1988; Warfvinge and Sverdrup 1988a, b), additional research is needed to better define and improve these mitigative liming techniques.

Only a minimal database exists from lakes with long histories of liming. Therefore, little knowledge exists regarding the potential long-term responses by lake ecosystems and their resident biota to operational liming programs. While little is actually known, much can be speculated about how liming affects these resources over scores of years. In particular, we have few data showing long-term changes/impacts in the non-fish aquatic community. Perhaps most importantly, we do not have data showing whether the invertebrate food bases for fish will stabilize over the long term in operationally limed lakes (Evans 1989). Then, because our of limited understanding on the response by the food base, our knowledge about the growth potentials for fish in these limed systems remains speculative. Finally, the ability to accurately predict appropriate liming and reliming dose rates are limited by the imprecise knowledge of actual lake volumes, runoff volumes, retention times, and acidic inputs.

Overall, many of the limitations and uncertainties associated with operational liming may be surmounted as more experience is gained through its use. However, we can benefit from this experience only if a strong continued commitment is made to monitoring the results produced in the limed lakes and streams, that is, to watching the changes realized in water chemistries and the responses shown not only by resident fish but by other aquatic biota and terrestrial wildlife.

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16. Abstract (Limit: 200 words)

This report provides state agencies and private landowners with guidelines useful in evaluating general options available for lake liming and for managing brook trout populations in limed lakes. It begins with a presentation of considerations necessary to determine whether to lime a lake, describing those lake types appropriate for liming and the limitations of liming. Approaches are discussed for determining the appropriate timing and dosages of basic materials to use for liming and reliming lakes. It next summarizes results from the "Extensive Evaluation of Lake Liming, Restocking Strategies, and Fish Population Response in Acidic Lakes Following Neutralization by Liming" which was conducted by researchers from Cornell University and sponsored by the U.S. Fish and Wildlife Service and the U.S. Environmental Protection Agency. The report then considers appropriate stocking and management strategies for brook trout in limed Adirondack lakes. While this report focuses primarily on neutralizing acidic lakes in the Adirondack region, many of the management implications can be extrapolated to other areas.

17. Document Analysis a. Descriptors

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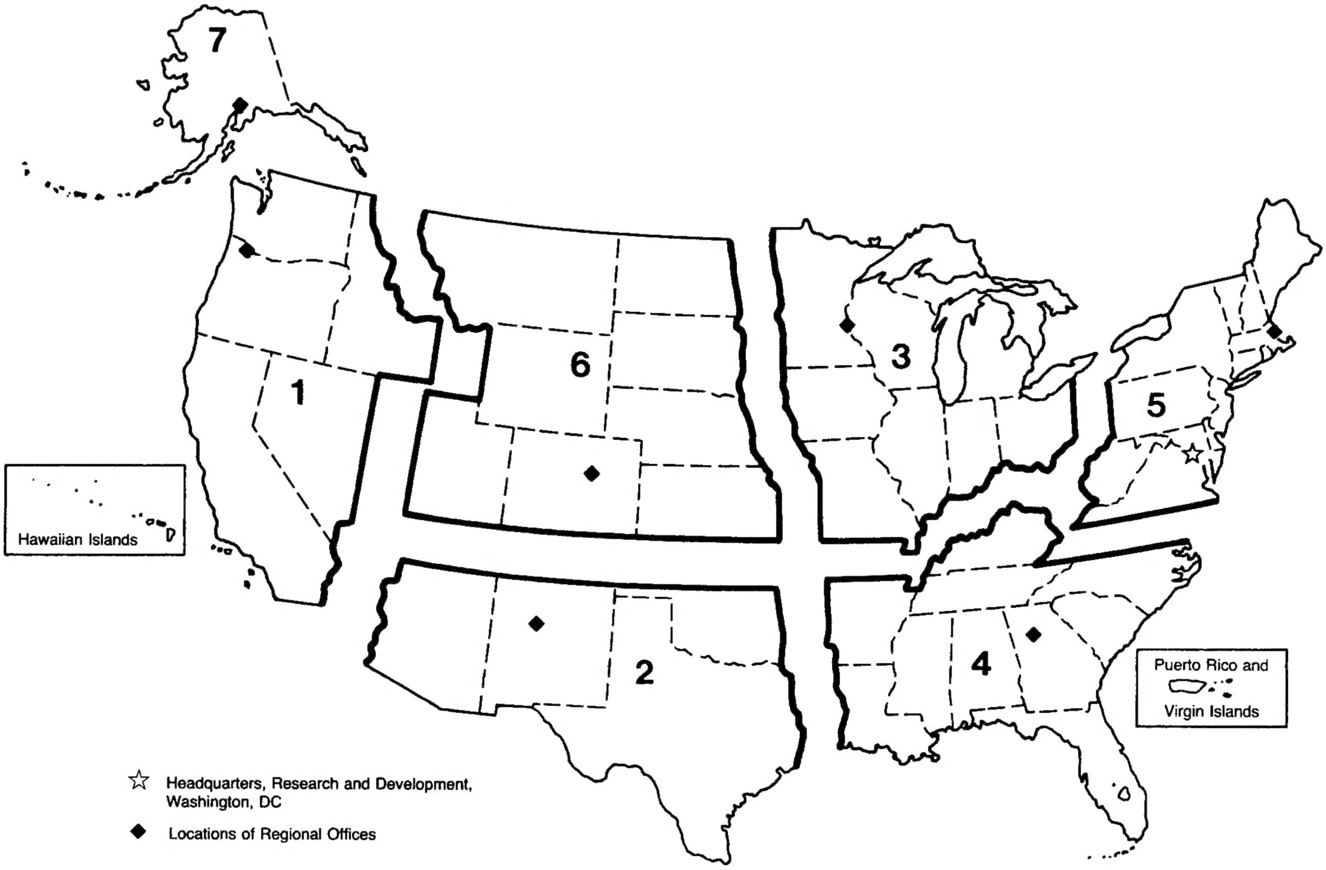

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